Final Performance Report

Reporting Period: May 1, 2021- October 31, 2024

Project Title: Developing a Cost-Effective Green Technology for In-Place Reclamation of Coal Mine Spoil Gob Piles in Abandoned Mine Lands

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Executive Summary

Mine spoils from coal mining activities accumulated as gob piles are difficult to reclaim due to constraints such as a steep slope, unsuitable pH, insufficient nutrient supply, metal toxicity, low water holding capacity, and poor soil structure. Reclamation of gob piles is often cost-prohibitive due to the lack of viable low-cost reclamation methods. This project aimed to develop, optimize, and demonstrate a low-cost, in-place sustainable reclamation technology on a field-scale using recycled organics (biochar and composts) for revegetation and stabilization of gob piles of mine spoils in the Carthage coalfield (CCF) in New Mexico. Project objectives were met via the implementation of four sequential tasks: (1) procurement and characterization of spoil materials, biochar, and composts; (2) incubation studies to identify the ideal mix of biochar/mine spoils and compost/mine spoils to generate the optimal water-holding and nutrient-holding capacity of the spoils without significant leaching of metals; (3) a greenhouse study to develop a vegetative cap using a high-biomass metal-tolerant grass with a long and dense root system, vetiver (*Chrysopogon zizanioides*) in comparison with a native tall fescue grass (*Festuca arundinacea*) to minimize soil erosion and promote site stabilization; (4) a small-scale simulated field study using three 7.0 ft. × 8.0 ft. × 1.0 ft. custom-made wooden platforms that were set up under the natural environment (open to natural elements) in New Mexico Tech (NMT) campus in Socorro which is only a few miles from the Carthage coalfield site. During the incubation study mine spoil collected from CCF was incubated for 90 days with various rates of biochar, compost, and a 1:1 biochar: compost mix, to identify the ideal organic mix to generate the optimal water-holding and nutrient-holding capacity for the spoils. After the incubation study, the 1:1 biochar: compost mix was selected for the subsequent studies. The greenhouse study was performed at Michigan Technical University for six months. During the greenhouse study three wooden panels (4 ft × 3 ft × 1 ft) were filled with 5 inches of sand each. Five inches of soil was added on top of the sand in all the panels, which amounted to 90 kg. The soil in two of the panels was amended with a 7.5% mix of biochar and compost mixed in 1:1 ratio. The third panel was left unamended and labeled as control. The soil was maintained at 70% water holding capacity for 30 days and allowed to equilibrate with the amendment in the greenhouse. After the equilibration period, designated as time zero, one panel was planted with 15 vetiver slips. Tall fescue seeds were sown in the second panel. Periodic soil samples were collected from each panel and were tested for plant available nutrients and metal concentrations. Surface runoff and leachate samples were collected after overwatering. The water samples were analyzed for pH, total suspended

solids (TSS), and turbidity. After successful completion of the greenhouse study simulated field study was performed. During this phase three 7.0 ft. × 8.0 ft. × 1.0 ft. custom-made wooden platforms were built at NTU. Each panel is equipped with leachate and surface run-off collection systems. The panels were set up in such a way that they have the same slope as the Carthage coal gob pile. The panels were loaded with 5 inches of play sand and 5 inches of coal gob pile collected from the Carthage site. Three sets of panels were: (i) Vetiver + soil with amendment, (ii) Fescue + soil with amendment, and (3) Control (no plant and no amendment). The gob pile soil was mixed with biochar and compost amendment that was used in our previous greenhouse study (a 7.5% mix of biochar and compost mixed in 1:1 ratio). Periodic leachate and surface run-off samples were collected from both panels after each major rainfall event. Samples were analyzed for pH, turbidity, TSS, and metals. The study was performed for six months. Soil samples were collected periodically and were analyzed for pH and metal content. Results show that organic amendment of the gob spoil soil by both the biochar and the compost led to a significant increase in its water-holding capacity. Plant-available nitrogen content of the gob spoil soil increased from <200 mg N/kg to between 400 to 800 mg N/kg in the amended soil. The period of incubation was also a significant factor in the improvement of plant available nitrogen content. Plant-available phosphorus content also increased; compost amendment was more effective than biochar in increasing plant-available P. Metal content of the potentially toxic metals in the gob spoil soil was low, except Al and Fe. A geochemical speciation study confirmed that organic amendments did not cause a notable increase in the soluble or exchangeable forms of Fe or Al. This study provides crucial information that would help in optimizing a sustainable reclamation method for CCF. This study show that this sustainable and cost-effective reclamation method will be of value to OSMRE and will have tremendous technology transfer potential with the help of our project partner, New Mexico Abandoned Mine Land Program. The technology will attract the attention of regulatory agencies and the reclamation industry as a viable model to reclaim the many coal mine gob piles that are scattered around the Western region.

1. <u>Introduction</u>

Although coal mining is an important industry that supports the economy, it also causes tremendous landform disruption and habitat destruction. Disruption of the land produces tons of mining waste material (or spoils), much of which contains high amounts of metals and sulfide-containing minerals such as pyrite (Kossoff et al. 2014). There are several ways of managing coal mine spoils, but most often they are put into massive "gob piles" resembling hillocks. Currently, there are 20,000 to 50,000 abandoned mines in the United States, many of them characterized by these gob piles that are highly erosion-prone, thus serving as a major source of environmental pollution and habitat destruction downstream. The nature of spoil materials varies widely, both in physical composition and chemical characteristics. It also varies with geography, with spoils from the Appalachian region having more acid-generating capacity than those of the Western spoils. This is because most of the western coalbeds have low sulfur and ash contents and are of similar geologic age, Cretaceous through early Tertiary.

Regardless of their geological origin or geographic location, gob piles containing mine spoils are mostly characterized by materials that are texturally unsuitable to hold water or nutrients. Some older gob piles contain thin "topsoil" layers, which vary from clayey to sandy depending on the underlying rock type- shale or sandstone. Low organic matter (OM) levels has been identified as the most common problem in mine spoils, which leads to poor soil health for plant growth and soil microbial life (Pulford 1991, Castillejo and Castello 2010, Larney and Angers 2012). Mine spoils with low plant diversity are likely to cause a shortage of OM accumulation, which in turn leads to poor soil texture and structure (Castillejo and Castello 2010). Poor water-holding capacity (WHC), sediment erosion by wind and water, soil surface crusting, and cracking of soils are some of the adverse effects that result from poor spoil structure (Hossner and Hons 1992). Although annuals and sparse clumps of grasses may be observed on gob piles, stabilizing vegetation is difficult to establish either artificially or naturally, and they mostly remain bare (Narten et al. 1983).

Revegetation is complicated by a series of soil constraints including unsuitable pH, insufficient nutrient supply, metal toxicity, low water holding capacity, and poor soil structure (Dollhopf 1998, Semalulu 1998, Miekle, Barta et al. 1999). On these slopes, seeds or seedlings are more likely to be washed away or buried by eroding material. Hence, to make a gob pile suitable for vegetation, the textural and chemical characteristics of spoils need to be manipulated to a point where they can sustain plant growth. This process is termed “topsoiling.” Narten et al. (1983) define topsoiling as the reuse of the original spoils as all or part of the new growing medium in reclamation. For topsoiling to work for the re-establishment of vegetation, (1) the water- and nutrient-holding capacity needs to be improved through the addition of OM and (2) the metal toxicity of the spoils needs to be decreased using sorbents that help in reducing the plant availability of metals. This is especially important because the added OM could potentially further solubilize metals, resulting in increased toxicity that prevents the establishment of vegetation. While manipulating the soil is the key to restoration, purchasing topsoil is cost prohibitive. Therefore, it is important to develop inexpensive amendment strategies that could improve soil quality and aid in plant growth.

1.1. Study Area

Our study area was Carthage Coal field (CCF) located approximately 12 miles southeast of Socorro, NM, and 10 miles east of San Antonio, NM (figure 1A, B). The coalfield lies on the east flank of the Rio Grande Rift in a series of small fault blocks that contain the coal-bearing units. Over 2 million short tons of coal were produced from mines within the CCF from 1882-1963 (Hoffman and Hereford 2009). Mining at CCF was historically done by the San Pedro Coal and Coke, Carthage Coal/Carthage Fuel Company, and the Kinney mines. The demand for coal declined during The Great Depression, coupled with the introduction of newer and more affordable means to heat homes. Eventually, the rail operation from CCF was stopped in 1931 when coal mining was no longer profitable. Currently, CCF is full of gob piles that cannot support the growth of vegetation (figure 1C).

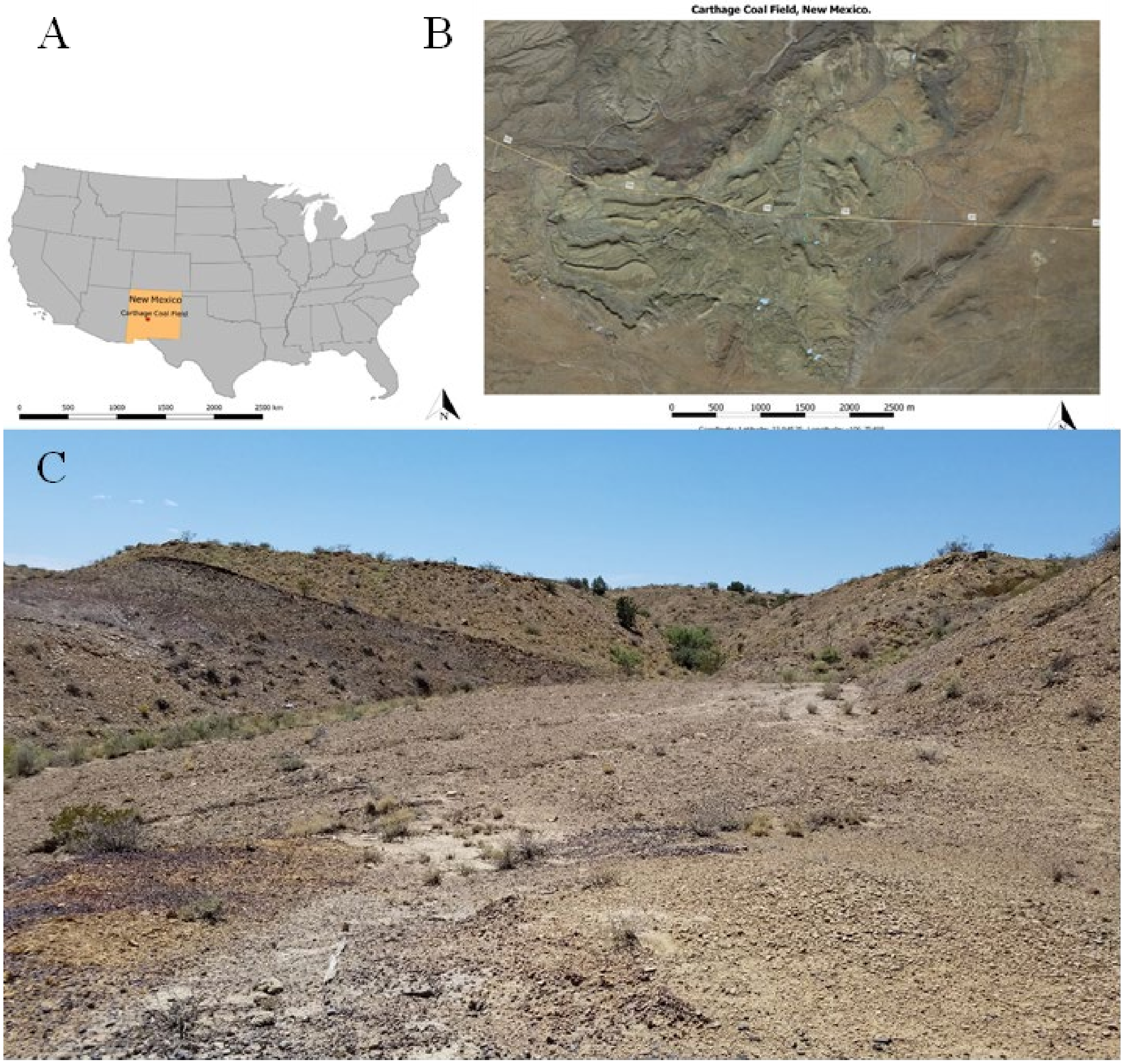


Figure 1. (A) Location of Carthage Coal Field (CCF) on the map of the United States, (B) the arc GIS map of the area, (C) Coal gob piles at CCF.

Project objectives were met via the implementation of four sequential tasks: (1) procurement and characterization of spoil materials, biochar, and composts; (2) incubation studies to identify the ideal mix of biochar/mine spoils and compost/mine spoils to generate the optimal water-holding and nutrient-holding capacity of the spoils without significant leaching of metals; (3) a greenhouse study to develop a vegetative cap using a high-biomass metal-tolerant grass with a long and dense root system, vetiver (*Chrysopogon zizanioides*) in comparison with a native tall fescue grass (*Festuca arundinacea*) to minimize soil erosion and promote site stabilization; (4) a small-scale simulated field study using three 7.0 ft. × 8.0 ft. × 1.0 ft. custom-made wooden platforms that were set up under the natural environment (open to natural elements) in New Mexico Tech (NMT) campus in Socorro which is only a few miles from the Carthage coalfield site.

2. Materials and Methods

2.1. Task 1. Material procurement and characterization

The Navajo Technical University (NTU) team consisting of the project PI, co-PI (NTU), and students visited the Carthage Coalfield (CCF) in July 2021. They were joined by four members from New Mexico Abandoned Mine Land Program (NMAML): Meghan McDonald, P.E., Principal Engineer, Joe Vinson, Project Manager, Richard Wessel, Cultural Resource Manager, and Leeland Murray, Project Manager. The NTU-NMAML team scouted various locations of CCF to select an ideal gob pile for this project. The gob pile was selected based on its slope, nature of gob materials, incident sunlight, and accessibility from the nearby road. The NTU team collected mine spoil samples following the standard USEPA procedure. Samples were stored in 32-gallon storage containers and were transported back to the NTU campus. The latitude and longitude of the selected gob pile were noted down and the measurement of the slope was conducted. Figures 2-4 show the selected site, sample collection process, and NTU-NMAML team in front of the selected area.

Figure 2. Coal gob pile in Carthage Coalfield (CCF), NM. Mine spoil samples were collected from this site and this site will also be used for field demonstration.

Figure 3. Measurement of the slope of the selected gob pile at CCF.

Figure 4: NTU-NMAML team at CCF.

At NTU the samples were properly labeled and stored securely until further use (Figure 5). The CCF spoil samples were air-dried, ground, sieved through 2mm sieves (Figure 6). Sieved samples were stored for all future experiments.

Figure 5: Samples were labeled and stored securely at NTU.

Figure 6: Carthage Coalfield (CCF) samples were air-dried, ground, sieved and stored until future use.

2.1.1. <u>Organic amendments</u>

Two organic amendments, biochar, and compost, were applied in this study. The biochar was produced following a local indigenous farming method. In this method, a 5 ft. deep and 4 ft. wide pit was dug in the ground, and burning coal was placed at the bottom of the pit. Coppiced stumps were placed in layers on top of the burning coal. Once the pit was full, it was covered with clay and soil such that the plant material was charred (figure 7). The charring process continued for 3 hours at 600°C. The temperature was monitored by inserting a Fisher brand Type-K Digital Thermometer probe inside the pit. After the pyrolysis process was completed, the biochar produced was shoveled out and allowed to cool. Finally, the biochar was ground using a mortar and pestle and the powder was used for this study. Commercially available compost (brand Garden Time Mushroom Compost®) purchased from a local hardware store was used for the study.

Figure 7. Biochar production from coppiced stumps following a local indigenous farming method at NTU campus.

2.1.2. Physicochemical characterization of the soil and amendments

Samples were shipped to Stevens Institute of Technology (SIT) for physicochemical analysis. Gob spoil soil and the organic amendments (biochar, and compost) were analyzed for their properties. Sample pH and electrical conductivity (EC) were measured following standard protocols using a Thermo Scientific Orion Star A215 Advanced pH/conductivity benchtop meter (Sparks, 1996). Water holding capacities were quantified by the modified Bernard method (Bernard 1963) as described in Govindasamy (2018). Organic matter content was measured by a loss-on-ignition method (Schulte and Hopkins 1996). Plant available N was determined by the sum of ammonium, nitrite, and nitrate that are available for plant uptake (Gianello and Bremner 1986, Stockdale and Rees 1994). Plant available P was analyzed by Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES, Agilent Technologies 5100) after Mehlich III extraction (Mehlich 1984). The total concentrations of metals (Ag, Al, As, Ba, Cd, Cr, Cu, Fe, Hg, Mn, Pb, and Se) in samples were measured using ICP-OES after acid digestion following USEPA Method 3050B (USEPA 1996). Sequential extraction of metals in mine gob spoil samples was done using Tessier et al (1979) method with a few modifications. Six geochemical fractions of metals (i.e., water-soluble F1, exchangeable F2, carbonate bound F3, oxides bound F4, organic bound F5, and residual silicate bound F6) in spoil samples were determined. Briefly, 1) 1 g oven-dried spoil sample was diluted with 15 mL deionized water, shaken at 250 rpm for 2 hours, and centrifuged at 3,500 g for 30 minutes to obtain the F1 fraction. 2) The residual spoil sample was extracted using 8 mL of 1 M $MgCl_2$ for 1 hour at room temperature for the exchangeable fraction (F2). 3) Extraction of the F3 fraction from the residual spoil sample from step 2 was done using 8 mL of 1 M CH_3COONa at pH 5.0 (adjusted using CH_3COOH) for 5 hours. 4) The oxide-bound metals (fraction F4) were extracted from the residual spoil sample obtained from the previous step with 20 mL of 0.04 M $NH_2OH{\cdot}HCl$ in 25% (v/v) CH_3COOH at 96 ˚C for 6 hours. 5) To extract the organic bound metals (fraction F5), 3 mL of 0.02 M HNO3 and 8 mL of 30% H_2O_2 (pH 2.0, adjusted with HNO_3) were added to the spoil sample from step 4 and the samples were incubated at 85˚C for 5 hours. After cooling, 5 mL of 3.2 M CH_3COONH_4 in 20% (v/v) HNO_3 was added. 6) The residual silicate bound metals (F6) was then obtained by digestion of the residual spoil sample from step 5 with concentrated HNO_3 at 105˚C. After each step, the supernatant was analyzed for metals using ICP-OES. Plant available metals were counted as the sum of fractions F1 and F2.

2.2. Task 2. Soil Incubation Study

Three sets of treatments were performed during the soil incubation study. For the first set of treatments, gob spoil soil was thoroughly mixed with compost at three rates (5%, 7.5%, and 10%, w/w). For the second set of treatments, gob spoil soil was thoroughly mixed with biochar at three rates (5%, 7.5%, and 10%, w/w). For the third set of treatments, compost and biochar were first mixed at a 1:1 ratio (mixed amendment), and then soil samples were amended with the mix at 5%, 7.5%, and 10% application rates (w/w) (table 1). For all treatments, 100 g of gob spoil soil with amendments were incubated in sealed polythene bags for 90 days. As a control, one batch of soil was incubated without any amendment. All soils were maintained at 70% of the soil's water-holding capacity at room temperature (RoyChowdhury et al. 2018). Periodic samplings were carried out on days 0, 7, 30, 60, and 90. All experiments were performed in triplicate.

Table 1. Soil Incubation Study Design. All experiments are carried out in triplicates. The total number of bags is 30.

Amendment Type	Amendment Rates (%)		
Compost	5	7.5	10
Biochars	5	7.5	10
Compost: Biochars (1:1)	5	7.5	10
Control	No amendments		

Figure 8. Soil Incubation Study at Navajo Technical University (NTU). A total of 30 bags containing compost and biochar amendments at different rates are being maintained at 70% of the soil water holding capacity. The incubation study will be conducted for 90 days.

Figure 9. Collection of day 0 (top) and day 7 (bottom) samples.

Figure 10. Collected samples were dried using a hot air oven.

2.2.1. Chemical analysis of incubated samples

Amended and unamended control soils were analyzed periodically for pH, EC, OM content, water-holding capacity, and plant-available N and P, as described in section 2.2. To obtain the geochemical forms of each metal in the samples, soil samples were sequentially extracted following the scheme established by (Tessier, Campbell et al. 1979). Six geochemical fractions (i.e., water-soluble F-1, exchangeable F-2, carbonate bound F-3, oxides bound F-4, organically bound F-5, and residual silicate bound F-6) were obtained. After each step, the supernatant was analyzed for metals (Ag, Al, As, Ba, Cd, Cr, Cu, Fe, Hg, Mn, Pb, and Se) using ICP-OES. The soil samples from each step were weighed and used in the sequential extraction procedure for the next step. The plant-available metals were calculated by combining water-soluble (F-1) and exchangeable (F-2) fractions.

2.2.2. Data analysis

Data analysis was performed using SPSS Statistics software. A one-way ANOVA was applied to analyze how the three sets of treatments affected the soil properties. The least significant difference test was performed to identify the statistical differences among different sets of treatments ($p<0.05$).

2.3. Task 3. Greenhouse Study

Greenhouse study was performed in Michigan Technological University (MTU) greenhouse facility. At NTU, more coal gob samples were sieved and ~300kg sieved coal gob samples were shipped to MTU (figure 11-12). Along with gob samples 10kg compost and 10kg biochar samples were also shipped to MTU for greenhouse study.

Figure 11. Coal gob samples were sieved to be shipped to Michigan Technological University (MTU).

Figure 12. Several batches of sieved samples (~300kg) were shipped from NTU to MTU for the greenhouse study.

At MTU, three wooden panels (4 ft × 3 ft × 1 ft) were filled with 5 inches of sand each (Figure 13). Five inches of soil was added on top of the sand in all the panels, which amounted to 90 kg. The soil in two of the panels was amended with a 7.5% mix of biochar and compost mixed in 1:1 ratio. The third panel was left unamended and labeled as control (C). The panels were constructed with a 10-degree incline, and a half-pipe was placed at the downslope end of the panel to divert runoff into a tank for collection. Two containers were attached to each panel to collect leachate from the soils. The bottom of the panel was covered with a mesh cloth to avoid soil loss into the leachate containers. The soil was maintained at 70% water holding capacity for 30 days and allowed to equilibrate with the amendment in the greenhouse at Michigan Tech.

After the equilibration period, designated as time zero, one panel (V) was planted with 15 vetiver slips which were previously grown in potting soil. The vetiver slips were removed from the potting soil, and the roots were washed thoroughly. The shoots were trimmed to 2 feet in length. The plants were weighed, measured, and planted in the panel. Tall fescue seeds were sown in the second panel (F) (figure 14).

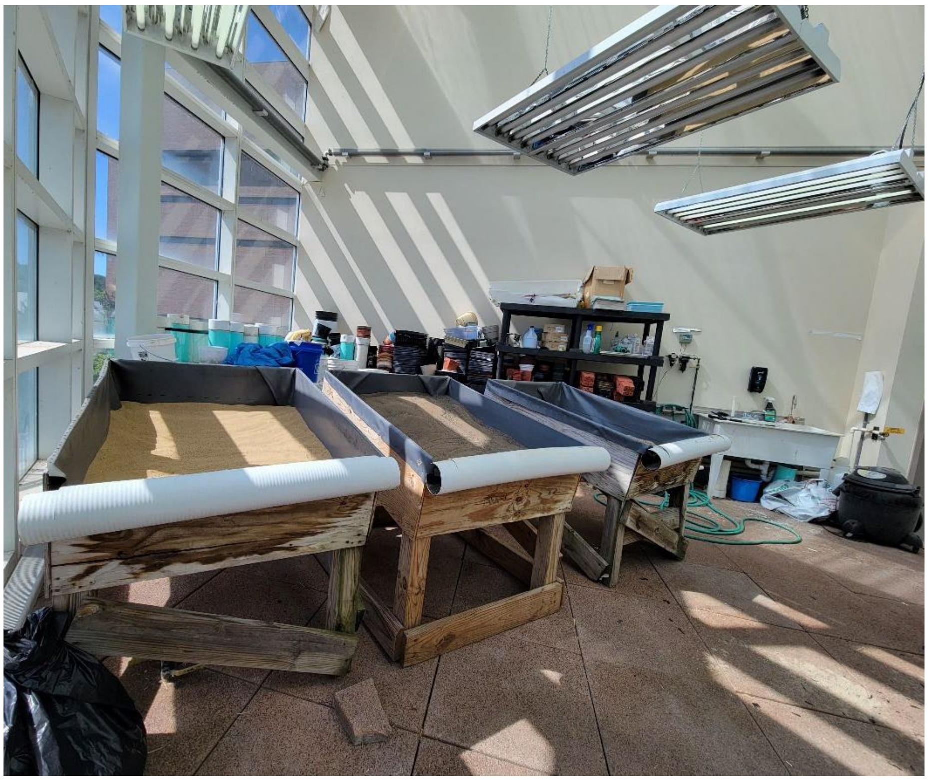


Figure 13. Three greenhouse study panels were set-up at Michigan Technological University.

Figure 14. Setup of panels in the greenhouse at Michigan Technological University.

The average fresh weight of the transplanted vetiver was 126 ± 7 gm. One vetiver plant at time zero was flash-frozen and stored at -80°C for chlorophyll estimation and enzyme analysis. Three vetiver plants were maintained in the potting soil as negative control (figure 15A). Tall fescue grass seeds were also sown in potting soil for comparison with mine soil (figure 15B).

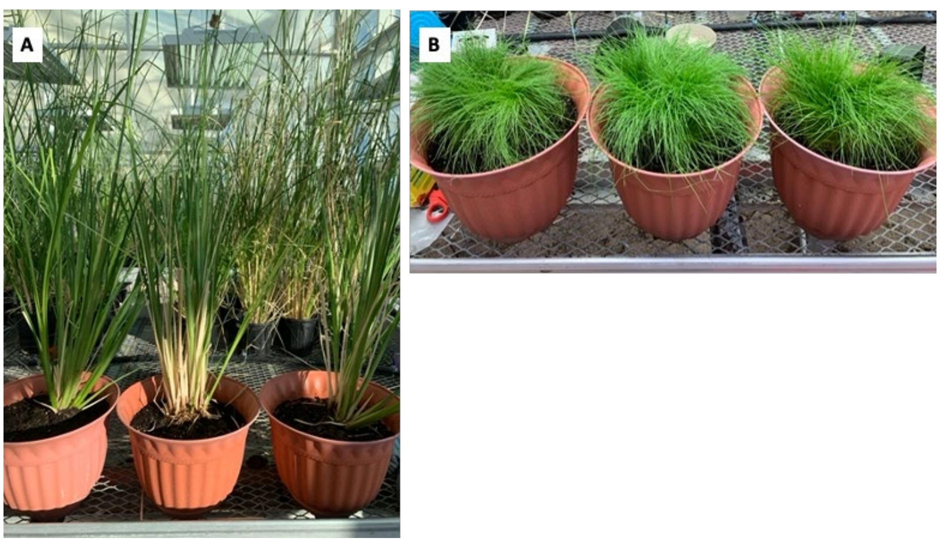


Figure 15. Vetiver (A) and tall fescue grass (B) growing in potting soil.

Time zero samples were collected from each panel and from the potting soil. After that the panels were overwatered once every 30days to simulate a rain event. The amount of water to be added per panel was determined by the average rainfall in New Mexico per month, the volume of the soil, and the area of the panel. The flow rate of water from the shower heads used for overwatering was calculated and 23L of water was added to each panel. Soil samples were collected from the panels after each simulated rain event. Surface runoff and leachate samples were collected after overwatering. The water samples were analyzed for pH, TSS, and turbidity. Soil and water samples were shipped to Stevens Institute of Technology for total and plant available metal analysis. Simulated rain events were conducted on 30days (M1), 60days (M2), 90days (M3), 120days (M4), and 150days (M5) after initial planting.

2.4. Task 4. Simulated Field Study

At NTU three 10.0 ft. × 10.0 ft. × 1.0 ft. custom-made wooden platforms were built for the simulated field study experiment. Each panel is equipped with leachate and surface run-off collection systems. After completion we hauled the panels to Socorro. The panels were assembled on site and have been set up in such a way that they have the same slope as the Carthage coal gob pile. The slope of the panels was controlled by adjusting the panel leg heights with cinder blocks.

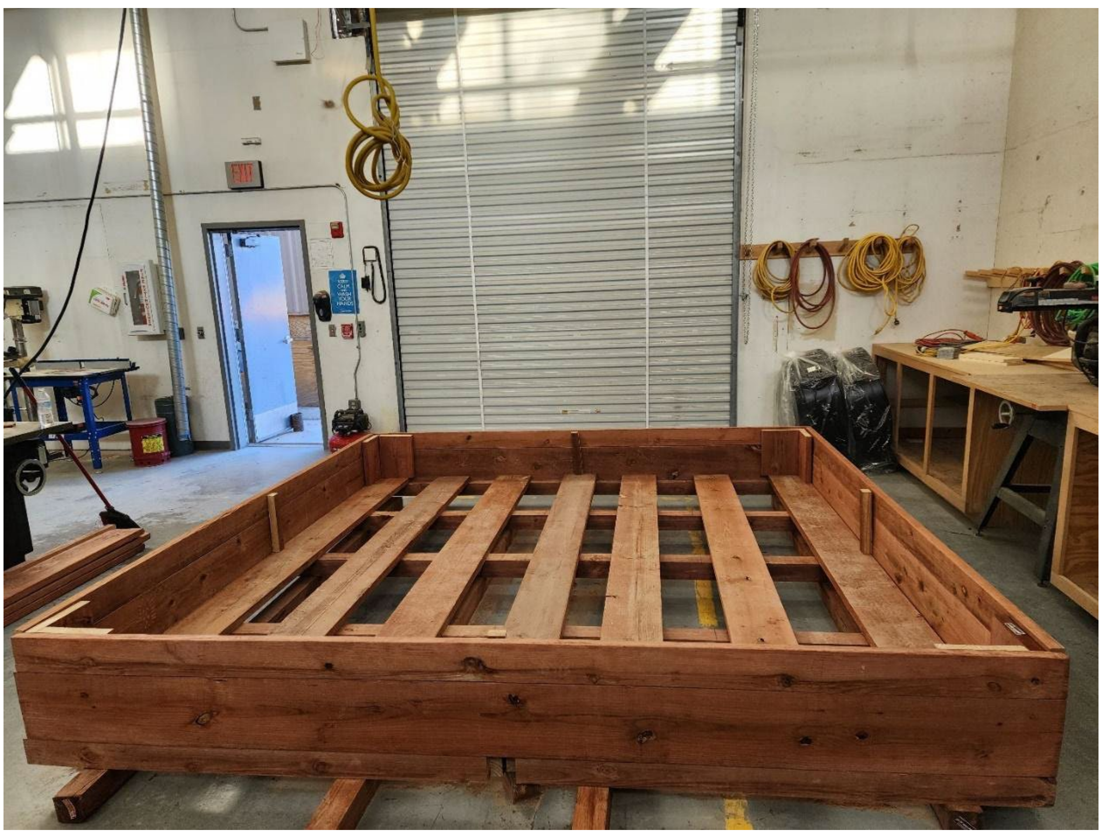


Figure 16. One of the 10.0 ft. × 10.0 ft. × 1.0 ft. custom-made wooden platforms that will be used for the revised simulated field study experiment.

Figure 17. Custom-made wooden platforms were hauled from Navajo Tech to New Mexico Tech campus in Socorro, NM (driving distance ~190 miles).

Figure 18. Custom-made wooden platforms arrived at New Mexico Tech campus in Socorro.

Figure 19. Navajo Tech students are assembling the custom-made wooden platforms in Socorro.

Figure 20. Navajo Tech students are assembling the custom-made wooden platforms in Socorro.

Figure 21. The slope of the wooden platforms was controlled by adjusting the panel leg heights with cinder blocks.

Figure 22. Each platform is equipped with leachate and surface run-off collection systems.

Figure 23. Three custom-made 10.0 ft. × 10.0 ft. × 1.0 ft. wooden platforms after complete assembly in Socorro.

The panels were loaded with 5 inches of play sand (figure 24) and 5 inches of coal gob pile collected from the Carthage site (figure 28).

Figure 24. Each panel were loaded with 5inches of play sand in the bottom.

We made several trips in between Carthage and Socorro to collect gob pile samples from the abandoned mine site (figures 26-27). The access to the site was given to us by the NMAML. Their staff members were present during our collection days. We went back to same gob pile from where we collected samples for our incubation and greenhouse studies earlier (figure 25).

Figure 25. Spoil samples were collected from the same gob pile from where the samples for incubation and greenhouse studies were collected earlier.

Figure 26. Samples were collected from Carthage gob pile.

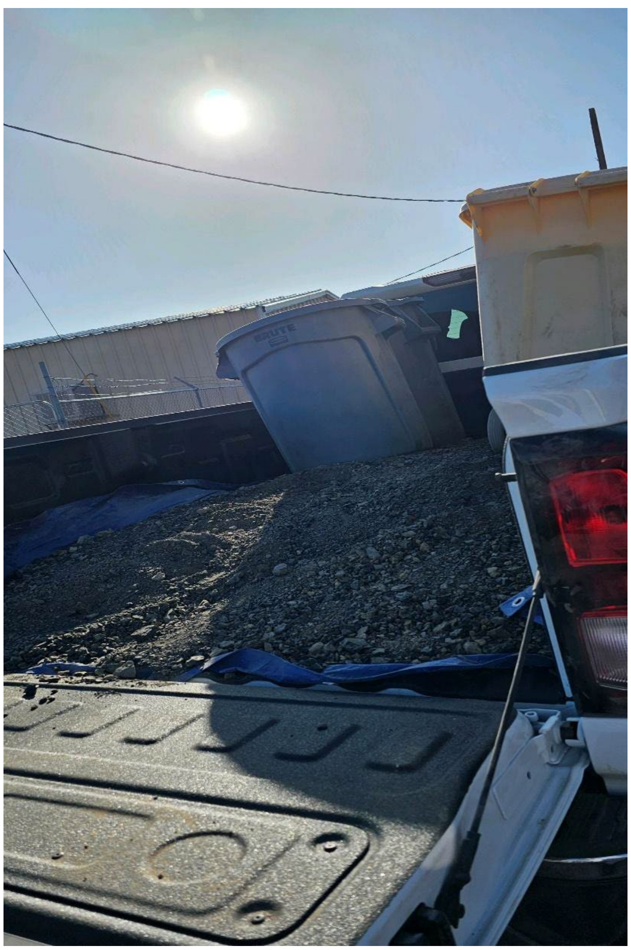


Figure 27. Collected samples were transported to Socorro from Carthage.

Figure 28. On top of the 5inches play sand 5inches of gob pile samples were dumped in each panel.

Three panels were set-up: (1) Vetiver + soil with amendment, (2) Tall fescue grass + soil with amendment, and (3) Control (no plant and no amendment). The gob pile soils were surface amended with biochar and compost amendment (in panels 1 and 2) that was used in our previous greenhouse study (a 7.5% mix of biochar and compost mixed in 1:1 ratio) (figures 29-30). For the vetiver panel 49 vetiver were planted (figure 31) keeping a 1ft distance between each other. 7 rows were established (figure 32). For the Tall fescue grass panel fescue seeds were spread by hand (figure 33).

Figure 29. Biochar and compost were mixed at 1:1 ratio to prepare the soil amendment.

Figure 30. Soil amendments (7.5% w/w rate) were surface applied in two panels.

Figure 31. Total 49 Vetiver were planted in the Vetiver panel (Panel 1).

Figure 32. Vetiver panel with 49 vetivers planted in 7 rows.

Figure 33. Tall Fescue seeds were hand spread in panel 2.

Figure 34. Three panels after completion of the set-up.

Figure 35. NTU students and faculty who set-up the field study in Socorro.

Periodic leachate and surface run-off samples were collected from the panels after each major rainfall events. Samples were analyzed for pH, turbidity, total suspended solids (TSS), and metals. The study was performed for six months. Soil samples were collected on day 0, day 60, day 90, and day 180, and were shipped to SIT for analysis.

3. Results and Discussion

3.1. Task 1. Material procurement and characterization

3.1.1. Physicochemical characteristics of soil and organic amendments

The gob spoil soil was near-neutral with a measured pH of 7.36 ± 0.07. While the pH of the compost was 7.81 ± 0.02, the pH of the biochar was basic at a pH of 9.70 ± 0.01 (table 2). The organic matter (OM) content of the soil was ~28%. Both the organic amendments had higher organic contents, ~86%, and ~49% for the biochar and the compost, respectively. Gob spoil soil was loamy sand in texture with 72% sand, 25.5% silt, and 2% clay (table 2) with only ~40% water holding capacity. The total P content of the soil was 131.78 mg/kg, but the plant available P content of the soil was low, at 37.34 mg/kg. On the other hand, the total and plant available P content of the biochar and the compost were comparatively much higher. For biochar, the total and Plant-available P contents were 528.22 mg/kg and 251.79 mg/kg respectively. For compost, the total and plant-available P were 3167.78 and 1770.80 (mg/kg soil), respectively (table 2). The total carbon content of the soil was 14.5%, whereas, for biochar and compost, the total carbon contents were 50.7% and 25% respectively (table 2). The RCRA 8 metal contents in the soil were low. Both the organic amendments showed comparatively low levels of RCRA 8 metal content and hence, were considered suitable for use as amendments for the gob spoil soil.

Table 2. Properties of the gob spoil soil, biochar, and compost samples used in this study.

Properties	Gob Spoil	Biochar	Compost
pH	7.36±0.07	9.70±0.01	7.81±0.02
EC (mS/cm)	3.783±0.012	3.29±0.089	10.05±0.34
Organic Matter Content (%)	27.75±0.83	86.43±0.58	49.31±2.11
Moisture Content (%)	3.79±0.09	9.37±0.27	39.27±0.80
Clay (%)	2.11±0.24	-	-
Silt (%)	25.51±1.03	-	-
Sand (%)	72.38±0.80	-	-
Water Holding Capacity (%)	40.0±4.0	-	-
Total C (%)	14.5±1.8	50.7±7.9	25.0±4.2
Total N (%)	0.3±0.03	0.2±0.02	1.8±0.22
Total P (mg/kg)	131.78±33.29	528.22±72.28	3167.78±227.94

Plant Available P (mg/kg)		37.34±6.20	251.79±21.59	1770.80±21.31
RCRA 8 metals (mg/kg, total)	**As**	2.43±0.29	0.64±0.14	1.22±0.08
	Ba	192.35±22.50	15.35±2.61	49.76±0.68
	Cd	0.65±0.09	BDL	0.19±0.01
	Cr	4.83±1.08	0.51±0.08	2.63±0.08
	Pb	7.76±2.08	0.39±0.12	0.59±0.18
	Hg	0.28±0.09	3.97±0.38	3.89±0.46
	Se	BDL	BDL	0.38±0.26
	Ag	0.17±0.11	BDL	BDL
Cu (mg/kg, total)		14.09±2.78	4.99±0.36	12.85±1.04
Fe (mg/kg, total)		7467±1217	546±105	2202±122
Al (mg/kg, total)		5414±1411	745±154	1803±71
Mn (mg/kg, total)		111±21	17±3	130±2

n=3 for all measurements

3.2. Task 2. Soil Incubation Study

3.2.1. Effects of Organic Amendments on soil pH and EC

The pH of the unamended soil decreased slightly from ~8.2 to below 8 within 7 days of incubation. Biochar amendment initially raised the soil pH above 8.5. However, the pH started decreasing with the passage of incubation time and stabilized at ~8.00 within 30 days. Subsequently, the pH remained stable for the remaining period (figure 36A). No substantial change in initial pH was observed for soils amended with either the compost or the mixed amendment ($p < 0.05$). No difference in soil pH trends was observed with changing amendment rates ($p > 0.05$). Overall, observable variations in soil pH with either the rate or the type of amendments were negligible, and the soil remained slightly basic (between pH 7.5 and 8.5). In general, organic amendments tend to decrease the soil pH (Naramabuye and Haynes 2006, Cui et al. 2008). However, as the starting pH of compost and biochar were neutral to basic, the amendment of the soil with either of them did not lead to a decrease in pH.

The EC of the unamended soil was much higher initially, at ~600 µS/cm (figure 36B). After 7 days of incubation, the EC decreased drastically to ~400 µS/cm. Beyond 7 days of incubation, the EC decreased at a slower rate to ~300 µS/cm. This decrease in the conductivity indicates that a larger fraction of the metals binds to OM over the incubation period leading to a lower fraction of free metals. Similar trends of EC were observed for soils with biochar amendments. In the case of soils with either the mixed amendment or only compost amendment, no clear trends were observed. This can be explained by the considerably lower OM content of the compost as compared to that of the biochar (table 2).

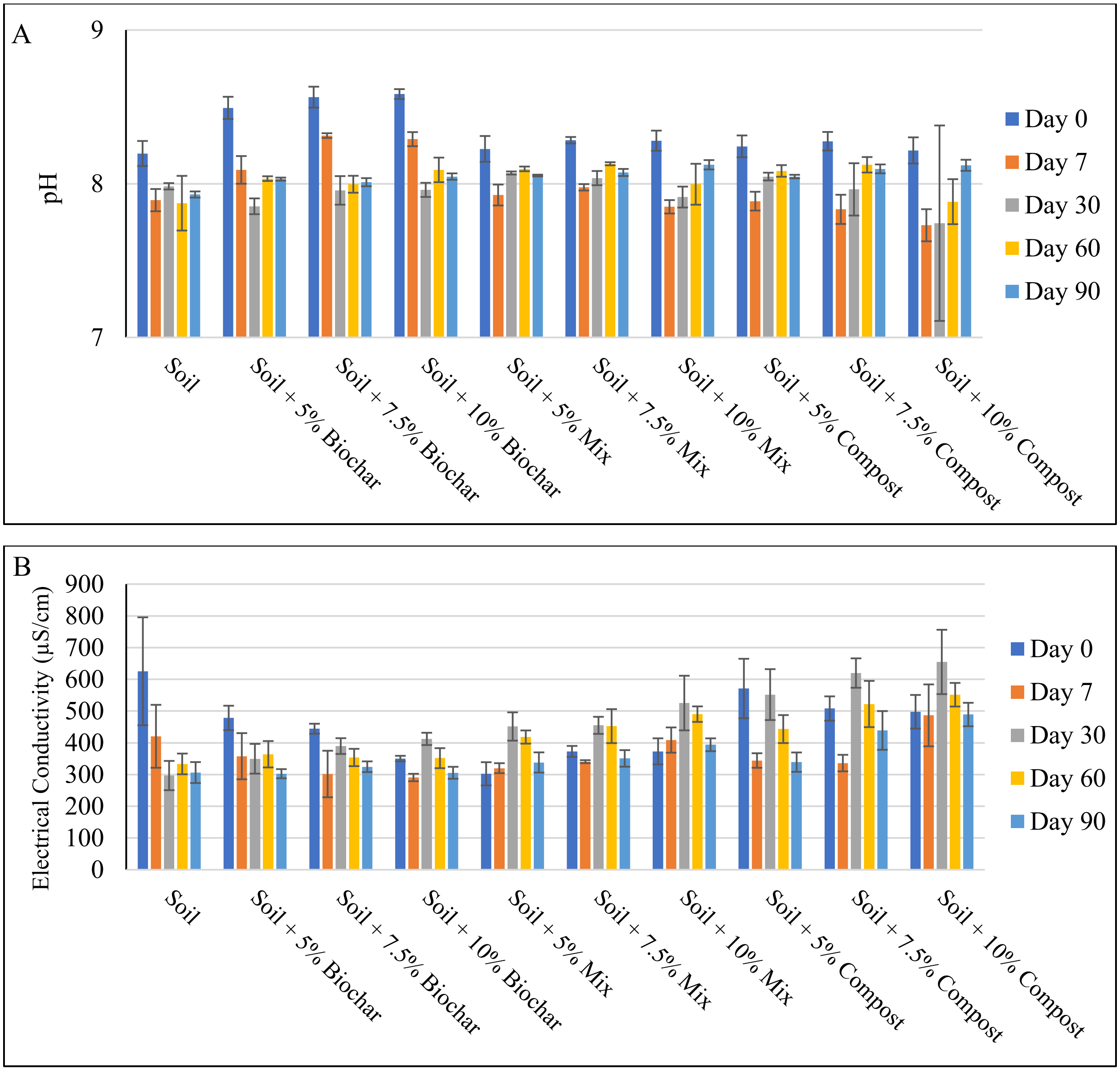
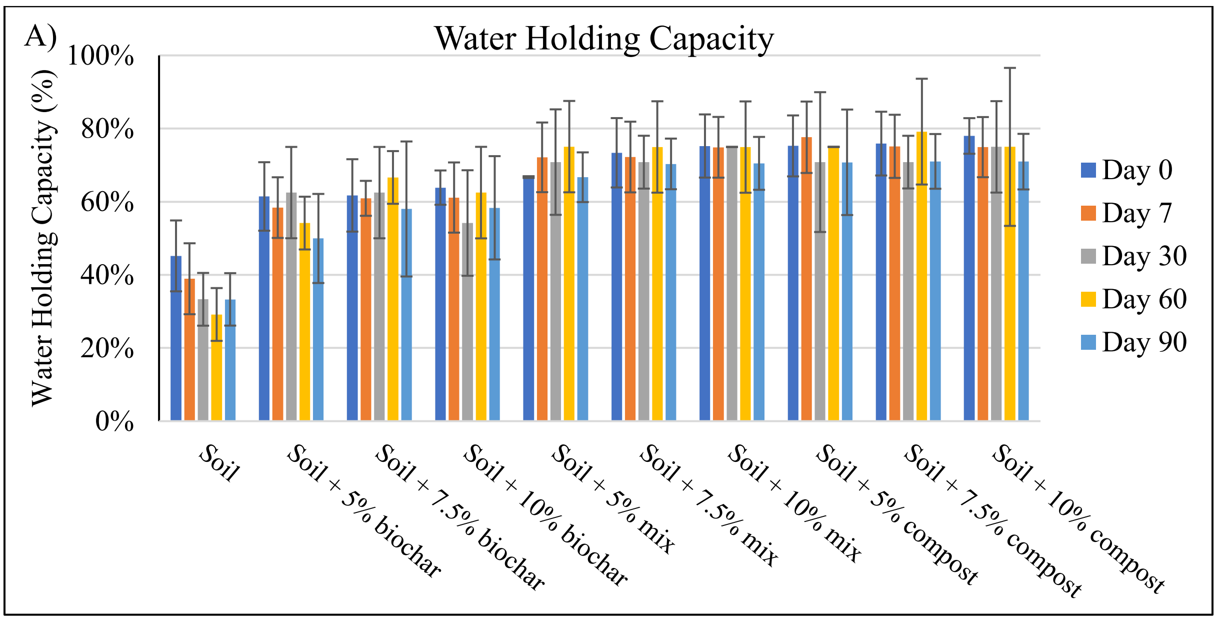


Figure 36. The impact of organic amendments on (A) soil pH; and (B) electrical conductivity. Data are shown as mean (n = 3) ± standard deviation.

3.2.2. Effects of organic amendments on soil water holding capacity

The soil water holding capacity is recognized as one of the most important parameters to facilitate vegetation and microbial activities (Lebourgeois et al. 2005, Bréda et al. 2006). However, the average water-holding capacity of the gob spoil soil was below 40% during the soil incubation study due to its loamy sand soil texture (figure 37A). Regardless of amendment rates, biochar increased the soil water holding capacity to approximately 60%, indicating a 50% increase. Biochar has been widely reported to enhance soil water holding capacity (Karhu et al. 2011, Basso et al. 2013, Yu et al. 2013, Verheijen et al. 2019). (Yu et al. 2013) reported that biochar generated from yellow pine scrap lumber could double the water-holding capacity of a loamy sand soil at an amendment rate of 9%. Although no significant differences ($p > 0.05$) were seen among the three biochar amendment rates (5%, 7.5%, and 10%) during the 90-day incubation period (table 2), the increase in water-holding capacity we observed (~50%) was slightly higher than the 38% reported in sandy soils, using red oak biochar amendment at 6% during a 91-day incubation (Basso et al. 2013). In comparison, both soils amended by compost or by the mixed amendment had average water-holding capacities at around 70%, which was not significantly higher ($p > 0.05$) than those amended by biochar only (figure 37A, table 3). Ghorbani et al. (2023) reported a better water-holding capacity by biochar under insufficient water stress in a field study, probably due to the increased soil aggregation and the porous structure of biochar. However, the efficiencies of biochar or compost in enhancing soil water holding capacity also depend on the types of biochar or compost used (Gonzalez and Cooperband 2002). In this study, all the treatments showed significant impacts ($p < 0.05$) on enhancing the water-holding capacity of the gob spoil soil (table 3).



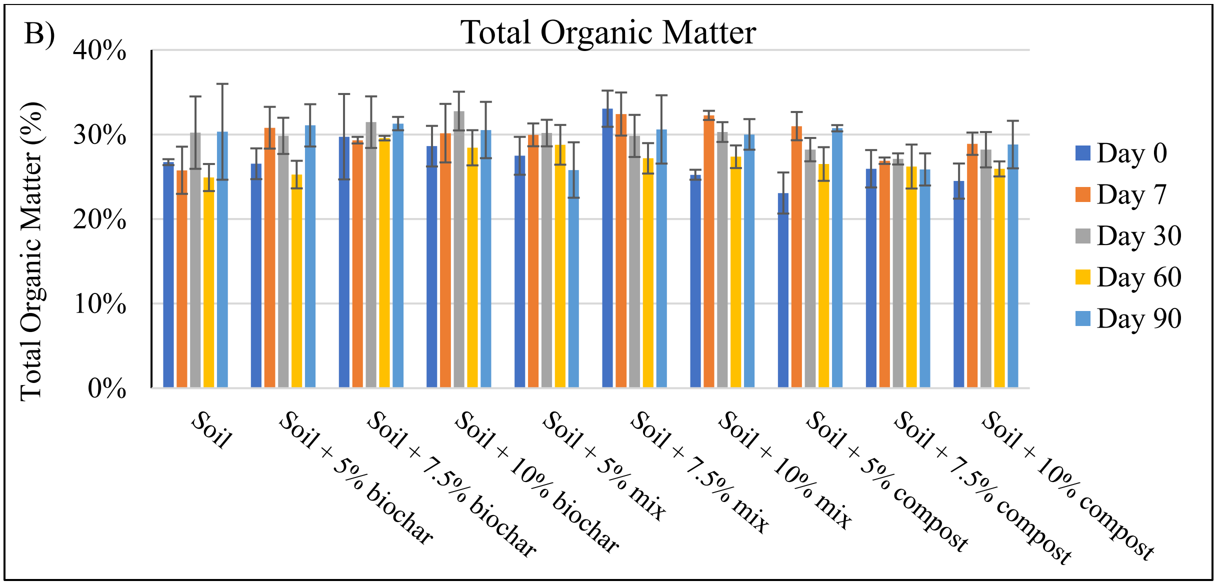


Figure 37. The impact of organic amendments on A) soil water holding capacity and B) soil organic matter. Data are shown as mean (n = 3) ± standard deviation.

Table 3. Statistical analytical results for soil amended with different amendments after 90 days of incubation.

Sample Type	Water Holding Capacity	Total Phosphorus	Plant Available Phosphorus	Plant Available Nitrogen
Soil	33.30±7.17 c	221.01±22.63 de	122.43±24.27 d	175.93±15.85 b
Soil + 5% biochar	49.95±12.18 bc	223.36±15.39 de	164.19±25.65 d	512.29±43.63 a
Soil + 7.5% biochar	70.33±6.92 a	216.12±23.98 e	168.26±21.70 d	598.36±87.94 a
Soil + 10% biochar	71.02±7.48 a	257.61±15.88 bcd	188.07±24.18 bc	665.57±68.67 a
Soil + 5% mix	58.01±18.46 b	238.56±21.59 de	184.10±12.16 cd	577.57±72.07 a
Soil + 7.5% mix	70.77±14.42 a	252.70±24.11 bcde	249.42±16.48 bcd	636.90±46.93 a
Soil + 10% mix	70.95±7.60 a	286.42±22.95 ab	255.93±10.51 ab	695.00±25.56 a
Soil + 5% compost	58.33±14.12 ab	242.87±11.93 cde	220.77±21.75 bcd	556.27±43.52 a
Soil + 7.5% compost	66.69±6.80 ab	279.81±22.88 abc	272.24±7.04 ab	627.70±7.55 a
Soil + 10 % compost	70.48±7.23 a	318.49±2.01 a	294.66±8.97 a	667.34±52.21 a

Note: Data are shown as mean (n = 3) ± standard deviation. Different letters in the same column correspond to statistically significant differences ($p < 0.05$).

3.2.3. Effects of organic amendments on soil organic matter and plant-available nutrients

The average OM in gob spoil soil ranged from 25% to 30% during the 90-day incubation period (figure 37B). The average OM percentage in soil did not show a significant ($p > 0.5$) increase in OM content after adding the amendments.

The availability of nutrients is an important indicator of soil quality. Nutrient depletion leads to soil chemical degradation as well as decreased vegetation cover (Lal 2015). The concentration of plant-available nitrogen in the gob spoil soil was below 200 mg N/kg during incubation (Figure 4A). This concentration significantly ($p < 0.05$) increased to approximately 500 mg N/kg after adding biochar at a 5% rate, which further increased to over 600 mg N/kg at higher biochar amendment rates at 7.5% and 10%. The increasing trend of plant-available nitrogen along with increased biochar amendment rates was similar to that of using compost as an amendment. By day 90, the average concentrations of plant-available nitrogen were 556, 628, and 667 mg N/kg for compost amendment rates at 5%, 7.5%, and 10 %, respectively (Figure 38A). Both biochar and compost increased nutrient availability for plants, which was consistent with previous literature (Ghorbani et al. 2023). For the mixed amendment treatment, the concentrations of plant available nitrogen by the end of the soil incubation study were 578, 637, and 695 mg N/kg at amendment rates of 5%, 7.5%, and 10%, respectively, which were similar to using biochar or compost alone as soil amendments (table 3).

As shown in Figure 38B, the addition of soil amendments significantly ($p < 0.05$) boosted the plant-available P in gob spoil soil (table 3). The average plant-available P in gob spoil soil was 122 mg P/kg without any soil amendment. This concentration increased by approximately 40, 50, and 70 mg P/kg after adding biochar at amendment rates of 5%, 7.5%, and 10% respectively. In comparison, more plant-available P was provided by the compost. After 90-days, the concentration increased by approximately 120, 140, and 160 mg P/kg at 5%, 7.5%, and 10% amendment rates, respectively. This can be explained by the concentration difference in plant-available P between biochar and compost, which were 252 and 1,771 mg P/kg, respectively. The average concentration of plant-available P was approximately 250 mg P/kg for the mixed amendment at a 7.5% or 10% rate.

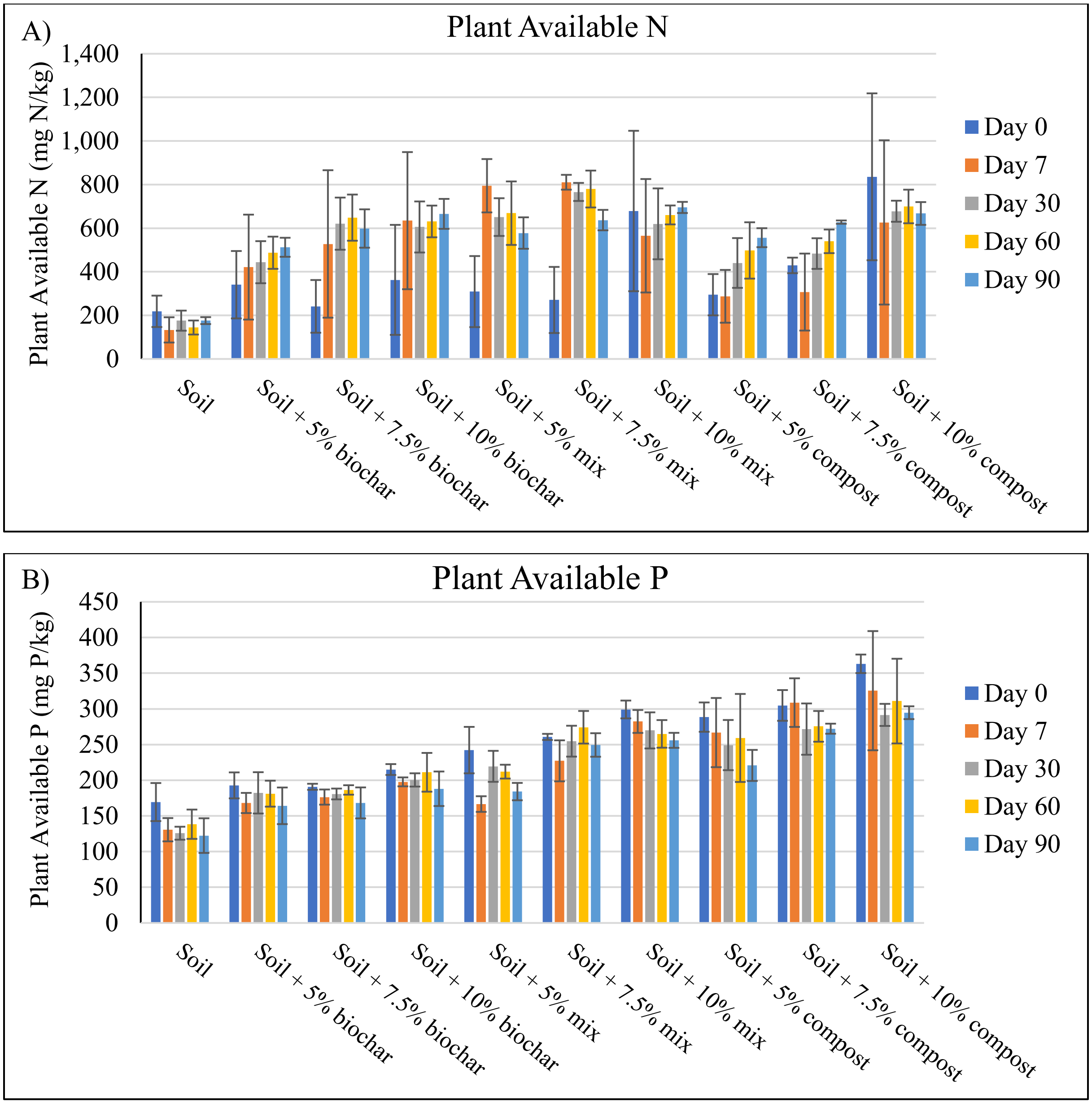


Figure 38. The impact of organic amendments on A) plant available nitrogen and B) plant available phosphorous. Data are shown as mean (n = 3) ± standard deviation

3.2.4. Effects of organic amendments on soil metals

The total concentrations of multiple metals, including Ag, Al, As, Ba, Cd, Cr, Cu, Fe, Hg, Mn, Pb, and Se, in soil samples with or without organic amendments, were quantified on days 0, 7, 30, 60, and 90 during the soil incubation study. Results showed that the concentrations of all metals were very low, except for Fe and Al (table 4). Due to the relatively high concentrations of Fe and Al in all soils, sequential extraction was done to study the geochemical fractionation of these two elements in the soil. The toxicity of metals depends on bioavailability, hence understanding the geochemical fractions of metals will provide a better understanding of the potential toxicity of these metals in soil (RoyChowdhury et al. 2018).

Geochemical fractions of Fe and Al on days 0 and 90 are shown in figure 39. Results showed that the water-soluble, exchangeable, and carbonate-bound Fe and Al were negligible in gob spoil soil on day 0 (figures 39A and 39C). The majority of the Fe present in the unamended soil was in oxides bound (17.5%), organic bound (7.5%), and residual silicate bound (74.9%) forms (figure 5A), while for Al, the corresponding percentages for these forms were 3.5%, 19.6, and 76.6%, respectively (Figure 39C). Figure 39A shows that the percentages of organic bound Fe in soils amended by compost (5.0%, 5.9%, and 5.8% for 5%, 7.5%, and 10%, amendment rates respectively) were slightly lower than the unamended soil. This is consistent with slightly lower total OM contents for compost-amended soil than that for the unamended soil (figure 37B). In comparison, biochar amended soil showed similar (at amendment rate 5%) or higher (at amendment rates 7.5% and 10%) organic bound Fe compared to the unamended gob spoil soil, which was also consistent with the trends in total OM results (figure 37B). The oxides bound Fe in gob spoil soil amended by 10% biochar was the highest among all treatments and the control. The two major geochemical fractions for Al were residual silicate bound and organic bound in gob spoil soil, followed by oxides bound for all samples. On day 0, the addition of biochar at 10% increased the percentages of oxides bound and organic bound Al, while all other organic amendment treatments did not significantly change the percentages of Al geochemical fractions compared to unamended gob spoil soil. By the end of the incubation period, the percentages of organic bound Fe for all organic amendment treatments increased compared to time zero (figure 39B). A similar trend was observed for Al in terms of the organic bound Al fractions (figure 39D). An insignificant increase in plant availability of Al (i.e., the sum of water-soluble and exchangeable forms of Al) was observed, but the percentages were very low at <2%.

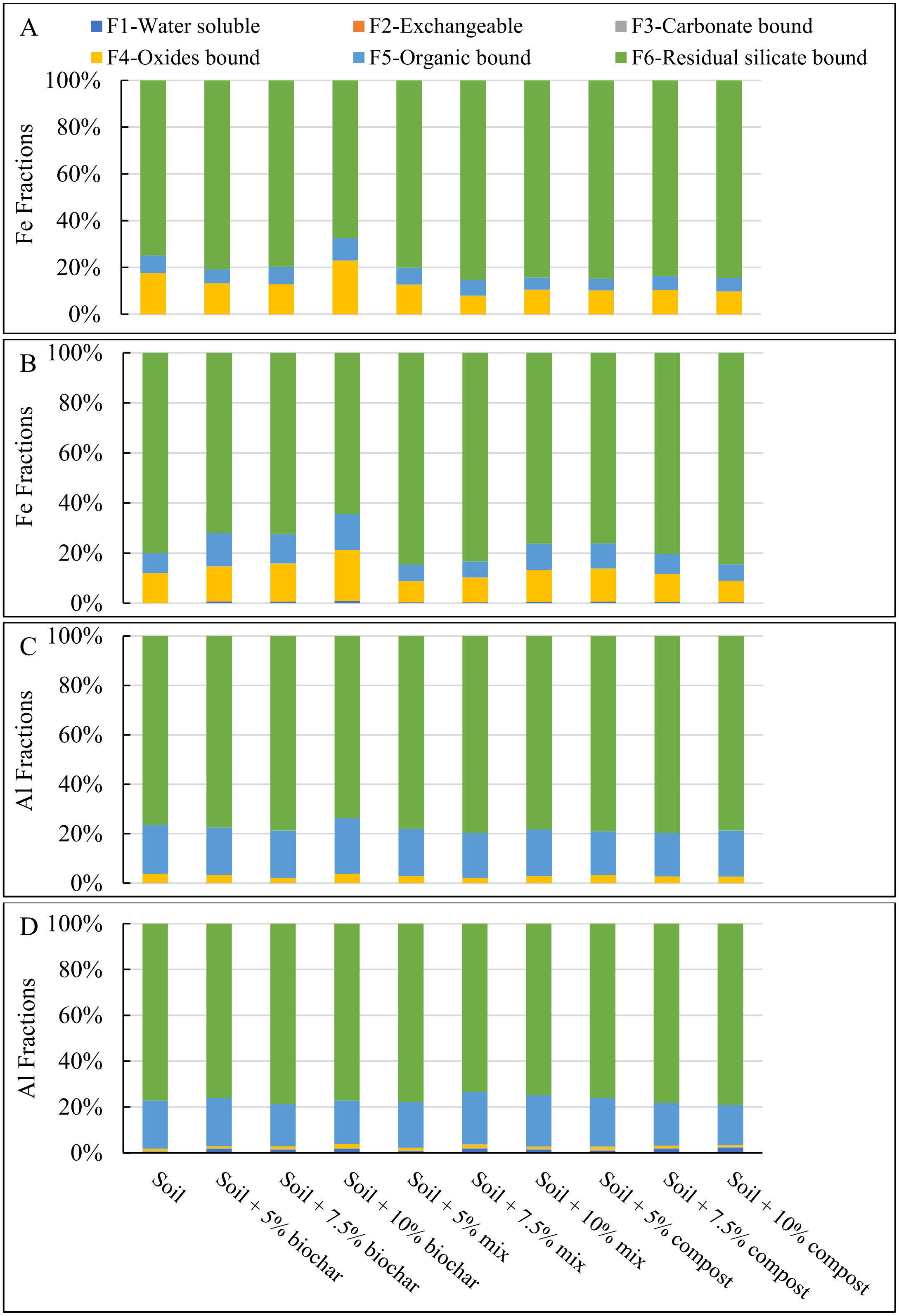


Figure 39. The impact of organic amendments on geochemical fractions of Fe and Al: A) Fe fractions on Day 0, B) Fe fractions on Day 90, C) Al fractions on Day 0, and D) Al fractions on Day 90.

Table 4. Total metal concentrations for soil incubation samples (mg/kg).

Samples		As	Ba	Cd	Cr	Pb	Hg	Se	Ag	Fe	Al	Cu	Mn
Day 0	Soil	6.26±2.06	385.82±148.30	1.46±0.04	8.96±0.11	14.29±1.23	4.13±0.76	BDL	BDL	16854±220	11724±379	21.27±0.52	231.75±40.18
	Soil + 5% biochar	4.31±1.48	236.45±14.04	1.10±0.24	7.62±0.74	10.23±2.93	2.53±0.21	BDL	BDL	13536±3238	9554±855	17.86±1.90	180.83±26.85
	Soil + 7.5% biochar	4.48±3.09	314.65±136.75	1.31±0.05	9.65±0.28	13.95±1.06	1.96±0.61	0.22±0.00	BDL	15905±354	12129±383	22.42±0.54	237.72±29.12
	Soil + 10% biochar	5.44±1.57	246.01±53.03	1.35±0.21	8.57±0.29	13.57±0.90	1.17±0.26	0.46±0.17	BDL	16134±1969	11152±549	20.43±1.25	246.85±45.14
	Soil + 5% mix	7.67±0.00	271.42±59.01	1.35±0.28	9.27±0.79	12.94±0.29	1.02±0.47	1.71±1.48	BDL	16393±3203	11677±1740	21.97±1.34	219.88±77.43
	Soil + 7.5% mix	4.99±3.60	359.24±184.27	1.21±0.26	8.54±1.28	11.98±3.24	0.86±0.42	3.29±0.88	BDL	14449±2662	10959±1645	20.68±3.05	189.71±52.66
	Soil + 10% mix	3.70±3.03	239.26±18.37	1.14±0.32	8.01±2.08	11.30±2.99	1.06±0.40	3.48±0.04	BDL	12860±3130	9839±2584	20.15±4.65	197.63±53.21
	Soil + 5% compost	3.30±2.91	232.95±25.14	1.19±0.09	8.92±0.53	12.93±0.55	0.63±0.26	1.22±0.66	BDL	14205±1216	10799±425	22.00±0.53	209.88±63.23
	Soil + 7.5% compost	5.29±2.72	212.20±135.05	0.85±0.61	6.19±3.17	7.77±6.68	0.44±0.22	1.24±0.46	BDL	9953±5741	7588±3400	14.83±10.12	159.10±51.31
	Soil + 10% compost	4.62±2.41	185.54±111.82	1.07±0.87	6.03±3.63	8.25±6.63	0.60±0.55	2.36±0.40	BDL	12202±9382	9057±1647	15.80±7.97	330.71±7.89
Day 7	Soil	5.58±2.64	364.59±254.01	1.40±0.04	9.33±0.59	14.93±0.24	0.30±0.13	BDL	BDL	16449±466	11292±1064	22.19±1.30	231.67±25.56
	Soil + 5% biochar	6.94±0.54	228.99±45.11	1.34±0.11	8.25±0.19	14.59±1.98	0.54±0.24	BDL	BDL	15179±714	9768±397	19.92±1.19	262.73±45.89
	Soil + 7.5% biochar	3.13±0.65	333.76±153.28	1.41±0.24	8.53±0.44	14.29±1.69	0.72±0.49	BDL	BDL	15120±1961	10390±782	22.73±1.03	209.13±4.55
	Soil + 10% biochar	4.11±2.02	285.39±99.23	1.31±0.15	8.52±0.51	11.89±2.05	0.52±0.30	BDL	BDL	15529±1952	10634±868	21.56±1.27	207.41±51.38
	Soil + 5% mix	6.45±3.35	280.38±34.32	1.37±0.37	8.39±0.28	12.32±1.62	0.40±0.18	1.81±0.26	BDL	16015±3267	10450±526	20.12±1.04	209.93±63.73
	Soil + 7.5% mix	4.13±3.78	227.63±77.44	1.11±0.10	8.29±0.49	12.66±1.98	0.41±0.33	2.00±0.00	BDL	13083±536	9997±364	20.42±0.49	177.57±59.16
	Soil + 10% mix	6.44±3.19	280.30±40.03	1.12±0.20	8.17±0.28	12.24±1.05	0.36±0.22	2.49±0.09	BDL	14019±2166	9903±652	21.14±0.45	205.54±20.76

	Soil + 5% compost	7.85±1.04	297.50±65.41	1.25±0.13	8.58±0.25	13.10±0.81	BDL	BDL	BDL	14801±545	10898±225	21.76±0.62	203.99±29.56
	Soil + 7.5% compost	5.00±3.65	258.03±57.38	1.29±0.23	8.37±0.86	12.44±1.16	0.43±0.21	1.75±0.15	BDL	15107±2956	10384±1324	21.65±1.64	190.34±36.88
	Soil + 10% compost	3.93±3.73	274.41±75.97	1.19±0.04	8.21±0.22	11.89±0.36	0.39±0.51	1.66±0.64	BDL	13471±329	9924±459	21.77±0.57	176.48±23.61
Day 30	**Soil**	3.07±0.85	288.55±43.49	1.53±0.11	8.19±0.39	12.13±0.49	1.41±0.74	0.72±0.00	0.14±0.02	13613±1238	8931±530	21.20±1.16	188.48±27.97
	Soil + 5% biochar	2.53±0.51	337.64±59.47	1.59±0.27	8.39±0.21	12.18±1.02	0.68±0.11	0.3±0.00	0.14±0.05	15207±2482	9658±152	21.36±0.61	183.29±28.6
	Soil + 7.5% biochar	4.61±1.06	384.32±47.91	1.64±0.20	8.43±0.34	12.68±0.16	2.54±1.22	0.20±0.13	0.15±0.09	15187±2495	9794±116	22.17±0.75	188.97±21
	Soil + 10% biochar	3.16±0.54	258.51±89.85	1.40±0.16	8.07±0.26	11.85±0.18	1.16±0.12	0.34±0.00	0.12±0.04	12896±1857	9514±509	20.76±0.93	150.36±15.4
	Soil + 5% mix	3.51±0.78	213.87±48.96	1.76±0.15	7.88±0.42	11.48±0.65	1.98±0.51	1.02±0.00	0.15±0.02	16263±1327	8674±651	20.51±0.73	190.28±34.15
	Soil + 7.5% mix	3.42±0.84	270.38±21.54	1.44±0.09	8.00±0.07	11.91±0.45	2.58±1.17	0.00±0.00	0.12±0.06	13436±1007	8895±378	21.60±0.08	164.55±37.55
	Soil + 10% mix	3.45±0.83	313.56±46.27	1.63±0.18	8.17±0.24	13.80±1.77	1.84±0.71	0.00±0.00	0.11±0.04	15371±1988	9336±582	22.71±1.20	250.36±49.74
	Soil + 5% compost	3.97±0.74	196.12±29.94	1.71±0.27	8.10±0.28	12.06±1.20	1.48±0.63	0.00±0.00	0.11±0.02	15995±2586	9470±361	22.68±2.40	227.87±65.35
	Soil + 7.5% compost	2.89±0.34	211.13±38.46	1.25±0.11	7.92±0.39	10.9±0.53	4.22±1.86	0.47±0.1	0.15±0.01	11719.14±1269.42	9325±583	21.39±1.27	141.76±17.32
	Soil + 10% compost	2.42±0.85	241.3±62.01	1.45±0.28	7.89±0.21	11.42±0.53	2.56±0	0.79±0	0.12±0.03	13490.43±2759.34	8807±302	22.04±1.42	171.99±43.11
Day 60	**Soil**	3.79±0.49	273.16±50.15	1.49±0.17	8.14±0.49	11.94±0.93	3.10±1.44	0.15±0.00	0.16±0.04	13823±1643	9091±1044.33	21.15±1.72	183.34±28.73
	Soil + 5% biochar	2.86±0.31	237.36±2.42	1.46±0.14	8.23±0.49	12.57±0.45	3.21±1.47	1.02±0.43	0.14±0.04	13751±1284	9681.67±286	22.19±2.27	194.54±38.41
	Soil + 7.5% biochar	3.55±0.57	285.36±95.27	1.44±0.07	8.20±0.34	11.82±0.74	4.86±2.65	0.02±0.00	0.17±0.04	13400±739	9703±598	21.62±0.51	211.92±46.65
	Soil + 10% biochar	3.07±0.85	249.89±33.73	1.41±0.09	8.21±0.47	11.35±0.95	3.68±1.28	0.45±0.02	0.19±0.11	13095±995	9371±391	22.36±2.07	187.49±21.85
	Soil + 5% mix	3.51±0.55	225.26±6.53	1.41±0.14	8.28±0.31	11.95±0.86	4.71±1.36	0.24±0.00	0.13±0.03	13167±1645	9894±845	21.95±2.40	171.80±20.67

	Soil + 7.5% mix	2.77±0.13	225.24±29.55	1.43±0.15	7.88±0.23	12.19±0.99	1.67±0.67	1.07±0.07	0.15±0.05	12998±1441	8632±602	22.04±0.80	172.05±12.27
	Soil + 10% mix	3.76±0.50	281.90±91.29	1.44±0.21	7.92±0.44	11.94±0.72	2.93±0.64	0.93±0.22	0.15±0.05	13211±1569	8854±889	21.45±1.85	189.80±11.72
	Soil + 5% compost	3.26±0.69	264.25±61.16	1.46±0.03	8.40±0.20	12.70±0.74	2.77±1.07	0.66±0.21	0.11±0.05	13548±229	9704±211	25.12±4.65	185.15±14.86
	Soil + 7.5% compost	3.04±0.95	216.00±40.41	1.47±0.13	8.06±0.31	11.26±0.69	2.73±0.87	0.45±0.23	0.19±0.03	13519±1063	8947±927	24.26±0.64	197.49±57.90
	Soil + 10% compost	3.32±0.73	250.02±15.22	1.54±0.12	8.18±0.23	12.90±0.96	3.31±0.39	0.00±0.00	0.16±0.05	13949±1605	9226±159	25.27±1.20	234.56±65.67
Day 90	**Soil**	3.89±0.59	224.17±16.29	1.10±0.15	7.64±0.84	11.97±1.37	2.76±0.91	0.54±0.00	0.11±0.03	13126±2229	8623±1303	21.14±2.46	179.38±28.28
	Soil + 5% biochar	2.81±1.16	230.00±29.66	1.11±0.18	7.43±0.01	11.57±0.56	3.04±0.86	0.51±0.01	0.12±0.05	13173±2629	8083±523	18.80±0.95	183.16±25.97
	Soil + 7.5% biochar	3.83±0.48	244.25±85.93	1.11±0.07	7.45±0.48	11.21±0.55	4.02±0.67	0.21±0.05	0.09±0.03	13700±766	8479±934	19.21±1.11	184.68±20.25
	Soil + 10% biochar	3.27±0.60	244.70±20.83	0.93±0.14	6.86±0.88	10.38±0.58	3.75±1.37	0.29±0.00	0.11±0.01	11245±1801	8309±915	18.37±2.18	183.30±30.91
	Soil + 5% mix	4.01±0.63	219.54±12.90	1.06±0.06	7.71±0.38	11.73±0.32	3.64±0.81	0.22±0.15	0.11±0.04	13156±1023	8744±606	20.75±1.28	177.65±23.68
	Soil + 7.5% mix	4.10±0.56	235.38±56.78	1.14±0.15	7.67±0.83	11.73±0.78	3.29±1.29	0.89±0.00	0.12±0.04	14153±2045	8548±1208	21.26±2.51	173.62±33.20
	Soil + 10% mix	3.69±0.39	255.06±5.34	1.04±0.11	7.29±0.67	11.23±1.11	3.82±0.98	0.60±0.00	0.08±0.03	12878±1596	8293±807	20.32±1.74	187.62±41.63
	Soil + 5% compost	3.79±0.79	244.23±24.49	1.18±0.06	8.16±0.73	13.00±0.91	3.81±0.35	0.22±0.09	0.10±0.02	14915±716	8733±575	23.00±1.40	181.44±13.21
	Soil + 7.5% compost	3.31±0.62	217.51±29.97	1.36±0.54	7.07±0.38	11.76±1.72	3.30±1.28	BDL	0.13±0.07	12779±1068	8112±533	19.43±1.79	199.80±38.83
	Soil + 10% compost	3.28±1.36	224.84±6.67	1.07±0.17	7.37±0.25	10.67±0.97	2.99±1.08	0.26±0.00	0.09±0.04	13029±2354	8570±1086	20.46±1.51	188.88±70.86

Note: Data are shown as mean (n = 3) ± standard deviation; BDL = Below Detection Limit.

3.3. Task 3. Greenhouse Study

During the greenhouse study both fescue and vetiver grass shown nice growth (figures 40-41). The pH of control panel was average ~8.1 during the study period where the average pH of fescue and vetiver panel was average ~8.08 and ~7.82 respectively (table 5).

Figure 40: Fescue grass panel after 4 months.

Figure 41: Vetiver grass panel after 4 months.

Table 5. pH, total suspended solid (TSS), and turbidity of leachate collected from each panel during the greenhouse study.

Sampling time	Type of sample	Soil pH (mean)	Leachate TSS (mg/L) (mean)	Leachate Turbidity (NTU) (mean)
Month 1 (M1)	Unplanted	8.16	27.25	317.5
	Vetiver	7.84	28.75	259.3
	Fescue	8.40	26.95	127.9
Month 2 (M2)	Unplanted	8.17	27.89	384.6
	Vetiver	7.84	24.89	260.5
	Fescue	8.18	24.76	125.7
Month 3 (M3)	Unplanted	8.28	25.86	374.90
	Vetiver	7.82	22.39	252.23
	Fescue	7.92	23.66	128.00
Month 4 (M4)	Unplanted	7.96	nd	344.57
	Vetiver	7.80	nd	118.2
	Fescue	7.92	nd	98.64
Month 5 (M5)	Unplanted	8.11	nd	351.92
	Vetiver	7.82	nd	110.8
	Fescue	7.98	nd	135.7

The availability of nutrients is an important indicator of soil quality. Addition of organic amendments increased plant available phosphorus (PAP) concentration in fescue and vetiver panels. The plant available phosphorus concentration ranged between 10 and 15 mg/kg in unamended control panel. PAP concentration increased to as high as 97 mg/kg and 103 mg/kg in vetiver and fescue panel respectively (table 6).

The average organic matter (OM) content in gob spoil soil was around 41.46% during the greenhouse study period (table 7). The average OM percentage in soil did not show a significant increase in OM content after adding the amendments.

Results from sequential extraction of soil samples showed that none of the metals are bioavailable as both water-soluble (F1) and exchangeable (F2) forms were above USEPA allowable level. These results proved that the addition of organic amendments didn't make metals present in the gob spoil soil bioavailable including Al and Fe (table 8-13).

Table 6. Total phosphorus and plant available phosphorus from each panel during the greenhouse study.

Sampling time	Type of sample	Total phosphorus (mg/kg)	Plant available phosphorus (mg/kg)
Month 0 (M0)	Unplanted	177.53 ± 20.62	10.76 ±1.45
	Vetiver	329.08 ± 20.81	54.39 ±3.11
	Fescue	450.56 ± 46.99	103.27 ±6.64
Month 1 (M1)	Unplanted	187.76 ± 23.52	15.37 ±2.08
	Vetiver	368.39 ± 5.84	62.02 ±2.49
	Fescue	371.82 ± 4.99	77.40 ±3.97
Month 2 (M2)	Unplanted	228.5 ± 17.6	12.96 ±4.25
	Vetiver	364.04 ± 20.4	62.76 ±3.56
	Fescue	421.66 ± 26.04	68.81 ±0.35
Month 3 (M3)	Unplanted	308.97 ± 53.28	14.27 ±0.86
	Vetiver	303.27 ± 84.34	97.65 ±1.79
	Fescue	351.02 ± 16.11	58.77 ±2.08
Month 4 (M4)	Unplanted	316.2 ± 12.74	12.75 ±1.35
	Vetiver	370.41 ± 15.23	54.10 ±4.70
	Fescue	301.78 ± 7.14	60.55 ±4.07
Month 5 (M5)	Unplanted	257.97 ± 29.06	15.61 ±1.19
	Vetiver	359.86 ± 8.17	61.71 ±0.89
	Fescue	440.23 ± 12.69	86.20 ±1.54

Table 7. Soil Organic Matter Content from each panel during the greenhouse study

Sampling time	Type of sample	Organic Matter Content (mg/kg)
Month 0 (M0)	Unplanted	33.46 ± 0.71
	Vetiver	21.89 ± 0.61
	Fescue	24.79 ± 1.27
Month 1 (M1)	Unplanted	52.22 ± 0.34
	Vetiver	25.11 ± 2.31
	Fescue	29.32 ± 5.89
Month 2 (M2)	Unplanted	48.63 ± 1.63
	Vetiver	24.46 ± 0.46
	Fescue	19.47 ± 4.80
Month 3 (M3)	Unplanted	22.35 ± 0.82
	Vetiver	23.58 ± 0.98
	Fescue	24.56 ± 0.74
Month 4 (M4)	Unplanted	19.32 ± 1.29
	Vetiver	23.64 ± 0.34
	Fescue	22.17 ± 1.72
Month 5 (M5)	Unplanted	31.32 ±3.63
	Vetiver	26.94 ± 3.11
	Fescue	26.14 ± 3.63

Table 8. Metal(s) concentration in soil samples in water-soluble form (F1) after sequential extraction.

	Sampling Time	Total metal concentration (mg/kg)											
	(Months)	Hg	As	Se	Zn	Cd	Pb	Ni	Fe	Mn	Cr	Cu	Al
Fescue	0	0.45 ± 0.42	0.15 ± 0.26	0.15 ± 0.26	0.10 ± 0.17	0.10 ± 0.17	0.10 ± 0.17	0.15 ± 0.26	0.05 ± 0.09	0.15 ± 0.26	0.05 ± 0.09	0.15 ± 0.26	0.60 ± 0.15
	1	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.30 ± 0.00
	2	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.10 ± 0.09	BDL	BDL	0.10 ± 0.09	0.30 ± 0.00
	3	BDL	0.10 ± 0.09	BDL	BDL	BDL	BDL	BDL	19.76 ± 4.35	BDL	BDL	0.30 ± 0.00	53.14 ± 11.80
	4	BDL	BDL	BDL	BDL	BDL	BDL	BDL	1.90 ± 0.98	BDL	BDL	0.15 ± 0.00	4.64 ± 2.21
	5	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.65 ± 0.38	BDL	BDL	0.45 ± 0.00	1.30 ± 0.23
Vetiver	0	BDL	0.05 ± 0.09	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.40 ± 0.09
	1	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.45 ± 0.00
	2	BDL	0.05 ± 0.09	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.45 ± 0.00
	3	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	0.50 ± 0.09
	4	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	0.50 ± 0.00
	5	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	0.50 ± 0.00
Unplanted	0	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09
	1	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.55 ± 0.09
	2	BDL	0.05 ± 0.09	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.60 ± 0.00
	3	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.40 ± 0.09
	4	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.30 ± 0.00
	5	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.05 ± 0.09	BDL	BDL	0.40 ± 0.09

[BDL= Below Method Detection Limit]

Table 9. Metal(s) concentration in soil samples in exchangeable form (F2) after sequential extraction

	Sampling Time	Total metal concentration (mg/kg)											
	(Months)	Hg	As	Se	Zn	Cd	Pb	Ni	Fe	Mn	Cr	Cu	Al
Fescue	0	BDL	0.1 ± 0.09	BDL	BDL	BDL	0.15 ± 0.00	0.15 ± 0.26	0.30 ± 0.52	0.3 ± 0.26	BDL	0.15 ± 0.00	2.49 ± 2.51
	1	BDL	0.15 ± 0.00	0.05 ± 0.09	BDL	BDL	0.15 ± 0.00	0.20 ± 0.09	BDL	BDL	BDL	0.15 ± 0.00	1.05 ± 0.30
	2	BDL	0.1 ± 0.05	0.05 ± 0.09	BDL	BDL	0.15 ± 0.00	0.15 ± 0.00	0.35 ± 0.38	0.35 ± 0.38	BDL	0.15 ± 0.00	2.85 ± 2.03
	3	BDL	0.10 ± 0.2	0.20 ± 0.09	BDL	BDL	0.10 ± 0.09	0.25 ± 0.09	0.70 ± 0.17	1.49 ± 0.15	BDL	0.25 ± 0.09	4.98 ± 1.00
	4	BDL	0.15 ± 0.00	0.10 ± 0.09	BDL	BDL	0.15 ± 0.00	0.20 ± 0.09	0.15 ± 0.15	2.20 ± 1.27	BDL	0.20 ± 0.09	2.20 ± 0.77
	5	BDL	0.1 ± 0.09	0.05 ± 0.09	BDL	BDL	0.05 ± 0.09	0.25 ± 0.09	0.25 ± 0.09	4.84 ± 0.92	BDL	0.45 ± 0.00	2.35 ± 0.62
Vetiver	0	BDL	0.15 ± 0.00	0.05 ± 0.09	BDL	BDL	0.10 ± 0.09	0.25 ± 0.09	0.25 ± 0.09	BDL	BDL	0.10 ± 0.09	2.80 ± 0.38
	1	BDL	0.10 ± 0.09	0.05 ± 0.09	BDL	BDL	0.15 ± 0.00	0.15 ± 0.00	0.35 ± 0.23	BDL	BDL	0.10 ± 0.09	3.49 ± 1.06
	2	BDL	0.10 ± 0.09	BDL	BDL	BDL	0.15 ± 0.00	0.15 ± 0.00	BDL	0.05 ± 0.09	BDL	0.15 ± 0.00	1.09 ± 0.37
	3	BDL	0.2 ± 0.09	0.05 ± 0.09	BDL	BDL	0.10 ± 0.09	0.20 ± 0.09	BDL	1.09 ± 0.17	BDL	0.15 ± 0.00	0.89 ± 0.15
	4	BDL	0.2 ± 0.09	BDL	BDL	BDL	0.15 ± 0.00	0.20 ± 0.09	0.05 ± 0.09	1.70 ± 0.77	BDL	0.15 ± 0.00	1.65 ± 0.54
	5	BDL	0.1 ± 0.09	0.10 ± 0.09	BDL	BDL	0.15 ± 0.00	0.15 ± 0.00	0.05 ± 0.09	0.35 ± 0.09	BDL	0.20 ± 0.09	1.44 ± 1.08
Unplanted	0	BDL	0.05 ± 0.09	0.10 ± 0.09	BDL	BDL	0.15 ± 0.00	0.15 ± 0.00	BDL	BDL	BDL	BDL	4.28 ± 6.00
	1	BDL	0.05 ± 0.09	0.15 ± 0.00	BDL	BDL	0.15 ± 0.00	0.15 ± 0.00	BDL	0.10 ± 0.09	BDL	0.10 ± 0.09	0.70 ± 0.09
	2	BDL	0.15 ± 0.00	0.10 ± 0.09	BDL	BDL	0.15 ± 0.00	0.25 ± 0.09	BDL	0.15 ± 0.00	BDL	0.30 ± 0.00	0.85 ± 0.09
	3	BDL	0.2 ± 0.09	0.15 ± 0.00	BDL	BDL	0.10 ± 0.09	0.20 ± 0.09	BDL	0.95 ± 0.23	BDL	0.15 ± 0.00	0.90 ± 0.40
	4	BDL	0.2 ± 0.17	0.05 ± 0.09	0.20 ± 0.09	BDL	0.15 ± 0.00	0.20 ± 0.09	4.44 ± 0.71	2.30 ± 0.09	BDL	0.20 ± 0.09	22.22 ± 2.70
	5	BDL	0.15 ±0.00	0.10 ± 0.09	BDL	BDL	0.15 ± 0.00	0.15 ± 0.00	0.70 ± 0.75	1.25 ± 0.23	BDL	0.05 ± 0.09	4.54 ± 3.98

[BDL= Below Method Detection Limit]

Table 10. Metal(s) concentration in soil samples in carbonate bound form (F3) after sequential extraction.

	Sampling Time	Total metal concentration (mg/kg)											
	(Months)	Hg	As	Se	Zn	Cd	Pb	Ni	Fe	Mn	Cr	Cu	Al
Fescue	0	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	BDL	BDL	BDL	0.50 ± 0.09
	1	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	BDL	BDL	BDL	0.30 ± 0.00
	2	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	BDL	BDL	0.15 ± 0.00	0.30 ± 0.00
	3	BDL	BDL	BDL	BDL	BDL	BDL	BDL	19.76 ± 4.35	BDL	BDL	0.30 ± 0.00	46.67 ± 14.48
	4	BDL	BDL	BDL	BDL	BDL	BDL	BDL	1.90 ± 0.97	BDL	BDL	0.15 ± 0.00	4.69 ± 2.19
	5	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.65 ± 0.38	BDL	BDL	0.45 ± 0.00	1.40 ± 0.09
Vetiver	0	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	BDL	BDL	0.15 ± 0.00	0.40 ± 0.09
	1	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	BDL	BDL	0.15 ± 0.00	0.35 ± 0.09
	2	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	BDL	BDL	BDL	0.35 ± 0.09
	3	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	BDL	BDL	0.15 ± 0.00	0.5 ± 0.09
	4	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	BDL	BDL	0.15 ± 0.00	0.60 ± 0.00
	5	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	BDL	BDL	0.15 ± 0.00	0.60 ± 0.00
Unplanted	0	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	BDL	BDL	BDL	0.25 ± 0.09
	1	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	BDL	BDL	BDL	0.55 ± 0.09
	2	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	BDL	BDL	BDL	0.60 ± 0.00
	3	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	BDL	BDL	BDL	0.40 ± 0.09
	4	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	BDL	BDL	BDL	0.30 ± 0.00
	5	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	BDL	BDL	BDL	0.40 ± 0.09

[BDL= Below Method Detection Limit]

Table 11. Metal(s) concentration in soil samples in oxides bound form (F4) after sequential extraction.

	Sampling Time	Total metal concentration (mg/kg)											
	(Months)	Hg	As	Se	Zn	Cd	Pb	Ni	Fe	Mn	Cr	Cu	Al
Fescue	0	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	BDL	0.3 ± 0.26	BDL	0.15 ± 0.00	2.50 ± 2.51
	1	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	BDL	0.05 ± 0.09	BDL	0.15 ± 0.00	1.10 ± 0.23
	2	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.35 ± 0.38	0.05 ± 0.09	BDL	0.15 ± 0.00	2.85 ±2.03
	3	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.70 ± 0.17	1.49 ± 0.15	BDL	0.25 ± 0.09	4.98 ± 1.00
	4	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.20 ± 0.09	2.20 ± 1.27	BDL	0.20 ± 0.09	2.20 ± 0.77
	5	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	3.89 ± 0.83	BDL	0.45 ± 0.00	2.35 ± 0.62
Vetiver	0	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	BDL	BDL	0.20 ± 0.09	2.80 ± 0.38
	1	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.35 ± 0.23	0.25 ± 0.09	BDL	0.15 ± 0.00	3.49 ± 1.06
	2	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	0.05 ± 0.09	BDL	0.15 ± 0.00	1.09 ± 0.37
	3	BDL	0.20 ± 0.09	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	1.09 ± 0.17	BDL	0.15 ± 0.00	0.89 ± 0.15
	4	BDL	0.20 ± 0.09	BDL	BDL	BDL	BDL	BDL	0.35 ± 0.23	1.70 ± 0.77	BDL	0.15 ± 0.00	1.65 ± 0.54
	5	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.20 ± 0.09	0.35 ± 0.09	BDL	0.20 ± 0.09	1.44 ± 1.08
Unplanted	0	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	BDL	BDL	0.20 ± 0.09	4.28 ± 6.00
	1	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.35 ± 0.23	0.10 ± 0.09	BDL	0.10 ± 0.09	0.70 ± 0.09
	2	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	0.15 ± 0.00	BDL	0.30 ± 0.00	0.85 ± 0.09
	3	BDL	0.20 ± 0.09	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	0.95 ± 0.23	BDL	0.15 ± 0.00	0.90 ± 0.40
	4	BDL	0.20 ± 0.09	BDL	BDL	BDL	BDL	BDL	0.30 ± 0.26	2.30 ± 0.09	BDL	0.20 ± 0.09	22.22 ± 2.71
	5	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.70 ± 0.75	1.25 ± 0.23	BDL	0.05 ± 0.09	4.54 ± 3.98

[BDL= Below Method Detection Limit]

Table 12. Metal(s) concentration in soil samples in organic matter bound form (F5) after sequential extraction.

	Sampling Time	Total metal concentration (mg/kg)											
	(Months)	Hg	As	Se	Zn	Cd	Pb	Ni	Fe	Mn	Cr	Cu	Al
Fescue	0	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	BDL	BDL	0.15 ± 0.26	0.65 ± 0.09
	1	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	BDL	BDL	BDL	0.30 ± 0.00
	2	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.00	BDL	BDL	0.10 ± 0.09	0.30 ± 0.00
	3	BDL	BDL	BDL	BDL	BDL	BDL	BDL	19.76 ± 4.35	BDL	BDL	0.30 ± 0.00	60.71 ± 4.54
	4	BDL	BDL	BDL	BDL	BDL	BDL	BDL	1.90 ± 0.98	BDL	BDL	0.15 ± 0.00	4.29 ± 1.65
	5	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.65 ± 0.38	BDL	BDL	0.45 ± 0.00	1.30 ± 0.23
Vetiver	0	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	BDL	BDL	0.15 ± 0.00	0.35 ± 0.09
	1	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	BDL	BDL	0.15 ± 0.00	0.45 ± 0.00
	2	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	BDL	BDL	0.15 ± 0.00	0.45 ± 0.00
	3	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	BDL	BDL	0.15 ± 0.00	0.50 ± 0.09
	4	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.30 ± 0.00	BDL	BDL	0.15 ± 0.00	0.60 ± 0.00
	5	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	BDL	BDL	0.15 ± 0.00	0.60 ± 0.00
Unplanted	0	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.30 ± 0.00	BDL	BDL	BDL	0.30 ± 0.00
	1	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.30 ± 0.00	BDL	BDL	BDL	0.50 ± 0.17
	2	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	BDL	BDL	BDL	0.55 ± 0.09
	3	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.30 ± 0.00	BDL	BDL	BDL	0.55 ± 0.09
	4	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	BDL	BDL	BDL	0.60 ± 0.00
	5	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.30 ± 0.00	BDL	BDL	BDL	0.60 ± 0.00

[BDL= Below Method Detection Limit]

Table 13. Metal(s) concentration in soil samples in residual matter bound form (F6) after sequential extraction.

	Sampling Time	Total metal concentration (mg/kg)											
	(Months)	Hg	As	Se	Zn	Cd	Pb	Ni	Fe	Mn	Cr	Cu	Al
Fescue	0	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.90 ± 0.00	0.30 ± 0.26	BDL	0.15 ± 0.00	0.95 ± 0.09
	1	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.90 ± 0.00	0.15 ± 0.00	BDL	0.15 ± 0.00	1.15 ± 0.23
	2	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.35 ± 0.38	0.15 ± 0.00	BDL	0.15 ± 0.00	2.90 ± 1.96
	3	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.70 ± 0.17	0.15 ± 0.15	BDL	0.25 ± 0.09	5.47 ± 0.88
	4	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.15 ± 0.15	2.20 ± 1.27	BDL	0.20 ± 0.09	2.25 ± 0.79
	5	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	4.84 ± 0.92	BDL	0.45 ± 0.00	2.20 ± 0.88
Vetiver	0	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	0.15 ± 0.00	BDL	0.20 ± 0.09	2.90 ± 0.53
	1	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.35 ± 0.23	0.15 ± 0.00	BDL	0.15 ± 0.00	3.39 ± 0.83
	2	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	0.15 ± 0.00	BDL	0.15 ± 0.00	1.04 ± 0.45
	3	BDL	0.25 ± 0.09	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	1.09 ± 0.17	BDL	0.15 ± 0.00	0.89 ± 0.15
	4	BDL	0.20 ± 0.09	BDL	BDL	BDL	BDL	BDL	0.35 ± 0.23	1.70 ± 0.77	BDL	0.15 ± 0.00	1.40 ± 0.74
	5	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.20 ± 0.09	0.35 ± 0.09	BDL	0.20 ± 0.09	1.49 ± 1.03
Unplanted	0	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	0.30 ± 0.00	BDL	0.20 ± 0.09	0.90 ± 0.00
	1	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.35 ± 0.23	0.30 ± 0.00	BDL	0.10 ± 0.09	0.80 ± 0.09
	2	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	0.15 ± 0.00	BDL	0.30 ± 0.00	0.85 ± 0.09
	3	BDL	0.20 ± 0.09	BDL	BDL	BDL	BDL	BDL	0.25 ± 0.09	0.95 ± 0.23	BDL	0.15 ± 0.00	0.90 ± 0.40
	4	BDL	0.30 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.30 ± 0.26	2.30 ± 0.09	BDL	0.20 ± 0.09	0.60 ± 0.00
	5	BDL	0.15 ± 0.00	BDL	BDL	BDL	BDL	BDL	0.75 ± 0.69	1.25 ± 0.23	BDL	0.15 ± 0.00	1.15 ± 0.38

[BDL= Below Method Detection Limit]

3.4. Task 4. Simulated Field Study

During the field study vetiver grass showed resilience and survived in the harsh environment. On the other hand, germination of fescue grass seeds didn't happen as expected (figure 42). Unlike the greenhouse study, all three panels were under natural conditions, and rainfall during the summer months (2024) were well below average and it was a dry and hot climate during the study period. Nevertheless, the response of vetiver to this condition was very satisfactory.

Similar to the previous two tasks, the average organic matter (OM) content in gob spoil soil ranged from 16% to 28% during the simulated field study period (figure 43). The average OM percentage in soil did not show a significant ($p > 0.5$) increase in OM content after adding the amendments. The maximum OM content was registered in the vetiver panel.

Figure 42. Vetiver (left) and Fescue grass (right) panels after one month of the simulated field study.

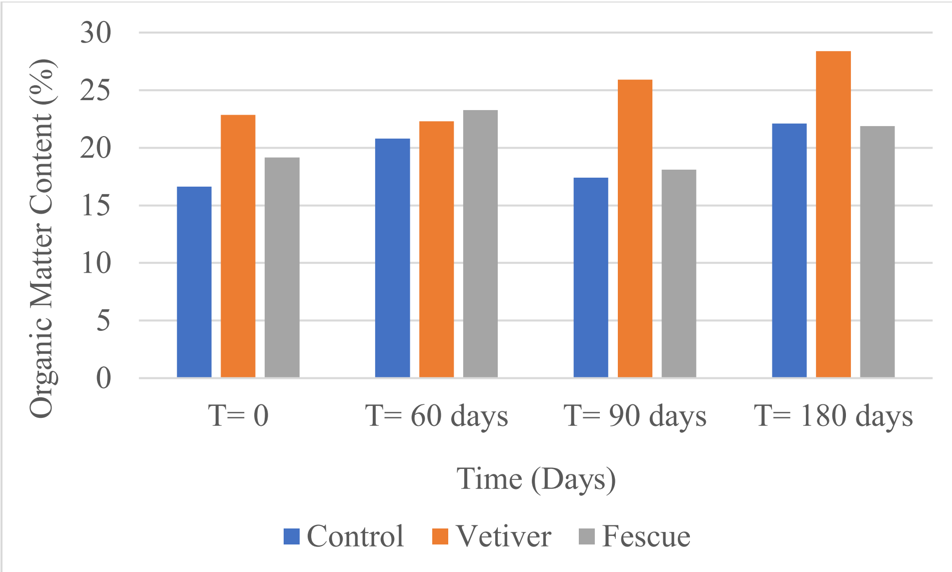


Figure 43. Change in organic matter content in three panels during the simulated field study.

The availability of nutrients is an important indicator of soil quality. Nutrient depletion leads to soil chemical degradation as well as decreased vegetation cover (Lal 2015). The concentration of plant-available nitrogen in the gob spoil soil was below 30 mg/kg nitrate in unamended soil. Addition of organic amendments increased the nitrate concentration to 113 mg/kg in fescue grass panel and to 159 mg/kg in vetiver grass panel (table 14). Plant available phosphorus concentration increased from 18 mg/kg in unamended panel to 90 mg/kg and 184 mg/kg in fescue grass and vetiver grass panels respectively (table 14). It was clear from the results that the addition of organic amendments significantly ($p < 0.05$) boosted the plant-available P in gob spoil soil. Vetiver grass was utilizing both plant available nitrogen and phosphorus to grow during the simulated field study.

The total concentrations of multiple metals, including As, Ba, Cd, Cr, Cu, Hg, Mn, Pb, and Se, in soil samples with or without organic amendments, were quantified on days 0, 60, 90, and 180 during the soil incubation study. Results showed that the concentration of all metals was very low (table 15) except for Al and Fe (table 16). Although the soil contains high concentrations of Al and Fe, our previous tasks showed that the bioavailable fraction of those two metals are very low. Leachate samples collected from each panel on day 60, 90, and 180 validated that observation as no significant Al and Fe concentrations were found in leachate samples (table 17).

Table 14. Nitrate and plant available phosphorus (PAP) in soil samples during the simulated field study.

	Sampling Time	Nitrate (mg/kg)	PAP (mg/kg)
Control	Day 0	29.44 ± 1.95	18.03 ± 0.86
	Day 60	101.60 ± 1.99	11.67 ± 0.56
	Day 90	65.74 ± 3.32	9.87 ± 0.55
	Day 180	84.55 ± 0.89	6.07 ± 3.02
Fescue Grass	Day 0	34.22 ± 1.42	16.87 ± 1.94
	Day 60	113.10 ± 4.65	90.20 ± 22.13
	Day 90	111.11 ± 11.51	84.43 ± 1.09
	Day 180	90.31 ± 2.21	70.60 ± 3.11
Vetiver	Day 0	78.13 ± 11.29	40.47 ± 0.33
	Day 60	125.50 ± 6.86	87.57 ± 5.41
	Day 90	159.59 ± 1.55	184.20 ± 3.52
	Day 180	102.92 ± 1.11	143.57 ± 1.59

Table 15. Metal(s) concentrations in soil samples during the simulated field study.

	Sampling Time	As (mg/kg)	Ba (mg/kg)	Cd (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Hg (mg/kg)	Mn (mg/kg)	Pb (mg/kg)	Se (mg/kg)
Control	Day 0	BDL	91.47 ± 8.75	BDL	11.00 ± 1.64	29.87 ± 2.80	BDL	109.53 ± 9.01	2190.67 ± 180.26	BDL
	Day 60	BDL	144.87 ± 7.01	BDL	10.67 ± 0.66	28.13 ± 2.22	BDL	115.73 ± 5.44	2314.67 ± 108.72	9.53 ± 5.86
	Day 90	BDL	115.00 ± 2.61	BDL	9.87 ± 0.94	26.07 ± 1.27	BDL	85.73 ± 3.04	1714.67 ± 60.85	BDL
	Day 180	BDL	170.13 ± 5.32	BDL	8.93 ± 0.41	19.87 ± 0.27	BDL	163.07± 1.66	3261.33 ± 33.17	1.13 ± 1.13
Fescue Grass	Day 0	BDL	285.67 ± 2.71	BDL	10.73 ± 0.58	28.93 ± 1.67	BDL	120.53 ± 5.09	2410.67 ± 101.73	4.73 ± 4.73
	Day 60	BDL	129.60 ± 3.88	BDL	9.93 ± 0.58	24.27 ± 0.27	BDL	97.87 ± 0.79	1957.33 ± 15.72	BDL
	Day 90	BDL	136.67 ± 10.16	BDL	13.00 ± 0.46	27.53 ± 3.35	BDL	97.13 ± 3.23	1942.67 ± 64.51	BDL
	Day 180	BDL	126.13 ± 2.37	BDL	10.07 ± 0.87	21.93 ± 0.64	BDL	88.87 ± 2.27	1777.33 ± 45.39	0.67 ± 0.67
Vetiver	Day 0	BDL	231.00 ± 14.14	BDL	12.40 ± 1.22	30.07 ± 1.46	BDL	106.40 ± 4.21	2128.00 ± 84.13	9.13 ± 9.13
	Day 60	BDL	211.00 ± 3.56	BDL	10.73 ± 0.81	24.20 ± 0.31	BDL	132.20 ± 0.46	2644.00 ± 9.24	11.53 ± 6.45
	Day 90	BDL	146.53 ± 11.21	BDL	28.47 ± 18.08	23.40 ± 0.31	BDL	125.60 ± 14.95	2512.00 ± 298.98	4.87 ± 3.64
	Day 180	BDL	177.47 ± 4.45	BDL	10.20 ± 0.31	21.00 ±0.70	BDL	119.07 ± 3.09	2381.33 ± 61.81	BDL

[BDL= Below Method Detection Limit]

Table 16. Aluminum and Iron concentration in soil samples during the simulated field study.

	Sampling Time	Al (mg/kg)	Fe (mg/kg)
Control	Day 0	13069.13 ± 1104.56	15316.73 ± 582.81
	Day 60	11823.8 ± 860.53	14098.07 ± 443.11
	Day 90	12328.53 ± 416.56	13595.67 ± 370.34
	Day 180	10612.6 ± 163.23	14478.4 ± 171.34
Fescue Grass	Day 0	12614.07 ± 312.26	13642.67 ± 128.07
	Day 60	12576.6 ± 731.76	12979.6 ± 229.10
	Day 90	16630.27 ± 881.63	13373.27 ± 364.17
	Day 180	12788.53 ± 724.05	11643 ± 157.21
Vetiver	Day 0	13712.93 ± 1353.88	12650.73 ± 414.46
	Day 60	13222 ± 363.17	13171.07 ± 19.07
	Day 90	12545.33 ± 1462.49	14837 ± 2127.50
	Day 180	13111.33 ± 170.01	11649.07 ± 355.98

Table 17. Aluminum and Iron concentration in leachate samples collected from the simulated field study.

	Sampling Time	Al (mg/L)	Fe (mg/L)
Control Panel-Leachate Sample	Day 60	0.06 ± 0.00	BDL
	Day 90	0.04 ± 0.00	BDL
	Day 180	0.03 ± 0.00	BDL
Fescue Panel-Leachate Sample	Day 60	0.09 ± 0.00	BDL
	Day 90	0.08 ± 0.01	BDL
	Day 180	0.07 ± 0.01	BDL
Vetiver Panel-Leachate Sample	Day 60	0.09 ± 0.00	BDL
	Day 90	0.07 ± 0.00	BDL
	Day 180	0.05 ± 0.00	BDL

[BDL= Below Method Detection Limit]

Conclusions

Organic amendment of the gob spoil soil by both biochar and compost led to a significant increase ($p < 0.05$) in its water-holding capacity leading to the enhancement in the soil quality for the growth of vegetation. No significant increase ($p > 0.05$) in the organic matter (OM) content of the gob spoil soil was observed due to the organic amendments. However, as the soil itself had a good amount of organic matter (~28%), any enhancement in OM content due to the amendments is not expected to make a big difference in soil fertility. On the other hand, the plant-available N and plant-available P content of the gob spoil soil was improved drastically due to the biochar and compost amendments. The potentially toxic trace metal content in the gob spoil soil was low and hence, any concern about organic amendments mobilizing toxic metals was negligible. The only exceptions were Al and Fe, which did not show a significant increase in soluble and exchangeable fractions, which are the plant-available forms of the metals.

Four undergraduate students (all of them are Native American) at NTU received hands-on training under the guidance of Dr. RoyChowdhury through this project. One of them (Ms. Kirby Morris) is currently pursuing a graduate degree at Northern Arizona University. Two postdoctoral fellows, Dr. Zhiming Zhang and Dr. Anshuman Satpathy, at Stevens Institute of Technology worked under the guidance of Dr. Sarkar for this project. Dr. Zhang is currently an Assistant Professor at Rowan University, and Dr. Satpathy is currently an Assistant Professor in Indian Institute of Technology (BHU), India. One PhD student, Ms. Roxana Rahmati, at Stevens Institute of Technology also worked under this project. One Master's student Ms. Kylee Hackman, worked under the supervision of Dr. Datta at MTU for this project. One peer-reviewed journal article has been published so far which was co-authored by the postdoctoral fellows from SIT and undergraduate student from NTU along with the project PI and co-PIs. Two conference presentations were also made by the project team. Future peer-reviewed publications and conference presentations are forthcoming.

References

Basso AS, Miguez FE, Laird DA, Horton R, Westgate M (2013) Assessing potential of biochar for increasing water-holding capacity of sandy soils. Gcb Bioenergy 5(2):132-143.

Bernard JM (1963). Forest floor moisture capacity of the New Jersey pine barrens. Ecology 44(3):574-576.

Bréda N, Huc R, Granier A, Dreyer E (2006). Temperate forest trees and stands under severe drought: a review of ecophysiological responses, adaptation processes and long-term consequences. Annals of Forest Science 63(6):625-644.

Castillejo JM, Castello R (2010) Influence of the application rate of an organic amendment (municipal solid waste [MSW] compost) on gypsum quarry rehabilitation in semiarid environments. Arid Land Research and Management 24(4):344-364.

Cui Y, Du X, Weng L, Zhu Y (2008) Effects of rice straw on the speciation of cadmium (Cd) and copper (Cu) in soils. Geoderma 146(1-2):370-377.

Dollhopf D (1998) Proceedings of 25th anniversary and 15th annual national meeting of the American Society for Surface Mining and Reclamation. Mining-gateway to the future.

Ghorbani MR, Neugschwandtner W, Konvalina, P, Asadi H, Kopecký M, Amirahmadi (2023) Comparative effects of biochar and compost applications on water holding capacity and crop yield of rice under evaporation stress: A two-year field study. Paddy and Water Environment 21(1):47-58.

Gianello C, Bremner J (1986) A simple chemical method of assessing potentially available organic nitrogen in soil. Communications in Soil Science and Plant Analysis 17(2):195-214.

Gonzalez R and Cooperband L (2002) Compost effects on soil physical properties and field nursery production. Compost Science & Utilization 10(3):226-237.

Govindasamy P (2018) Effect of Long-Term Tillage Practices on Soil Physico-Chemical Properties and Weed Population Dynamics in a 36-Year Old Experiment. Doctoral Dissertation, Texas A&M University.

Hoffman GK, Hereford JP (2009) Mining history of the Carthage coal field, Socorro County, New Mexico. Geology of the Chupadera Mesa: New Mexico Geological Society, Guidebook 60:407-413.

Hossner L, Hons F (1992) Reclamation of mine tailings. Soil Restoration: Soil Restoration 17:311-350.

Karhu K, Mattila T, Bergström I, Regina K (2011) Biochar addition to agricultural soil increased CH4 uptake and water holding capacity–Results from a short-term pilot field study. Agriculture, ecosystems & environment 140(1-2):309-313.

Kossoff D, Dubbin W, Alfredsson M, Edwards S, Macklin M, Hudson-Edwards KA (2014) Mine tailings dams: Characteristics, failure, environmental impacts, and remediation. Applied Geochemistry 51:229-245.

Lal R (2015) Restoring soil quality to mitigate soil degradation. Sustainability 7(5):5875-5895.

Larney FJ, Angers DA (2012) The role of organic amendments in soil reclamation: A review. Canadian Journal of Soil Science 92(1):19-38.

Lebourgeois F, Bréda N, Ulrich E, Granier A (2005) Climate-tree-growth relationships of European beech (Fagus sylvatica L.) in the French Permanent Plot Network (RENECOFOR). Trees 19:385-401.

Mehlich A (1984) Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Communications in Soil Science and Pant Analysis 15(12):1409-1416.

Miekle T, Barta L, Barta J (1999) Waste rock revegetation: Evaluation of nutrient and biological amendments. Proceedings 16th Annual National Meeting of the American Society for Surface Mining Reclamation, Scottsdale, AZ.

Naramabuye F, Haynes RJ (2006) Effect of organic amendments on soil pH and Al solubility and use of laboratory indices to predict their liming effect. Soil science 171(10):754-763.

Narten PF, Litner S, Allingham J, Foster L, Larsen D, McWreath H (1983) Reclamation of mined lands in the western coal region, US Geological Survey.

Pulford I (1991) Sewage sludge as an amendment for reclaimed colliery spoil. Alternative uses for Sewage Sludge, Proceedings of a Conference organised by WRc Medmenham, University of York, UK 41-54.

RoyChowdhury A, Sarkar D, and Datta R (2018) Preliminary studies on potential remediation of acid mine drainage-impacted soils by amendment with drinking-water treatment residuals. Remediation Journal 28(3):75-82.

Schulte E and Hopkins B (1996) Estimation of soil organic matter by weight loss-on-ignition. Soil organic matter: Analysis and interpretation 46:21-31.

Semalulu O, Barnhisel R, Witt S (1998). Vegetation Establishment on Soil-amended Weathered Fly Ash. Journal American Society of Mining and Reclamation. 722-731.

Sparks D, Page A, Helmke P, Loppert R, Soltanpour P, Tabatabai M, Johnston C, Summner M (1996). Methods of soil analysis: chemical methods, part 3. ASA and SSSA, Madison, WI.

Stockdale E, Rees R (1994) Relationships between biomass nitrogen and nitrogen extracted by other nitrogen availability methods. Soil Biology and Biochemistry 26(9):1213-1220.

Tessier A, Campbell PG, Bisson M (1979) Sequential extraction procedure for the speciation of particulate trace metals. Analytical chemistry 51(7):844-851.

USEPA (1996) Test methods for evaluating solid waste, SW 846, Third Edition. Office of Solid Waste and Emergency Response, Washington, DC.

Verheijen FG, Zhuravel A, Silva FC, Amaro A, Ben-Hur M, Keizer JJ (2019) The influence of biochar particle size and concentration on bulk density and maximum water holding capacity of sandy vs sandy loam soil in a column experiment. Geoderma 347:194-202.

Yu O-Y, Raichle B, Sink S (2013) Impact of biochar on the water holding capacity of loamy sand soil. International Journal of Energy and Environmental Engineering 4:1-9.